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PREFACE

This number, which concludes Volume 48 of the Quarterly TRANSACTIONS of the American Institute of Electrical Engineers, contains the papers and committee reports presented at the 1929 Summer Convention held at Swampscott, Massachusetts, June 24-28, and *The Engineer, Practical Idealist*, the address delivered by President Schuchardt at that convention.

Excitation of Current Transformers under Transient Conditions, by D. E. Marshall and P. O. Langguth, a paper read at the Cincinnati Regional Meeting but received too late to appear in the July Quarterly, is published here.

An index of authors and a subject index to Volume 48 are included in this issue.

“Synchronized at the Load”

A Symposium on New York City 60-Cycle Power System Connections

I. A Fundamental Plan of Power Supply
By A. H. KEHOE

II. Calculations of Systems Performance
By S. B. GRISCOM

III. System Tests and Operating Connections
By H. R. SEARING AND G. R. MILNE

REVIEW OF THE SUBJECT

Under our modern conditions it has become a common experience to have certain improvements adopted as necessities, although at some earlier time they would have been classed as extreme luxuries. Electrical service rendered by metropolitan public utility companies in recent years has evolved into one of these necessities due to the change in customs and in living conditions of the American people. In the initial stages of development, while the central station industry was taking the preliminary steps to establish itself in the commercial field, its product being expensive was purchased only where it could be indulged in as a luxury. During this period, methods of utilization of electrical service were very limited, being confined almost entirely to illumination. Such electric systems as existed were small, and the problem of their continuity was not of major importance. Disturbance and even interruption to customers' supply was a regrettable but not a vital incident. Cost of energy was the principal consideration rather than the reliability of supply, particularly where strong competition with other established forms of service was to be expected. As the art developed, many efforts were made to improve the quality of service in order to make a more salable product; nevertheless some interruptions were still experienced and were usually considered a necessary evil. With a much improved, but less expensive product, other competing methods of supply gradually became obsolete, leaving the central station alone in its field with an obligation to render the best possible service. Then interruptions could no longer be considered minor incidents.

Service to districts with high load density, such as the central portion of cities, very soon felt the effect of this requirement, and the demand was usually met by adopting systems of distribution which would give reliable service although at increased expense over other methods of supply, which, while much less costly,

could not offer the same degree of reliability. The influence of quality service had its effect on the requirements of these as well as other districts, and the entire elimination of service interruptions has everywhere been given the most serious consideration due to the dependence of the customer on a reliable service that will not cause interruptions resulting in serious inconvenience, economic loss, or possible hazard to life. Also there are many new types of utilization that are constantly being adopted as higher reliability with lower costs makes these available to all. With further reduction in costs, many other new applications are certain to arise. Thus, it follows that low-cost reliable service produces greater utilization which, in turn, makes it imperative to render still better service. This characteristic development is a feature of American life, and its counterpart in some form of material progress will be found to be the basis for most of the changes which have taken place in our modern customs. In the case of metropolitan central station companies, the huge concentrations of power required to provide the services which are a necessity for the normal life and business of the community, make the problem of reliability of supply at low system costs of vital importance to all.

The papers comprising this symposium present a new principle of decentralization of power sources and cover the investigation of a new plan of design and operation of a metropolitan power system. This arrangement is expected to provide the solution to the problem of reliability of supply and low system costs. The underlying ideas have been verified not only by experiments on one system but also by an extensive engineering analysis. Close agreement was observed between calculated and test results, and this should justify the use of the analytical methods outlined in applying the principles involved to the design of other power systems. The fundamental plan is described and the methods and results of calculations made are given. The symposium concludes with system tests and operating experience with the new arrangement of connections.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

“Synchronized at the Load”—I

A Fundamental Plan of Power Supply

BY A. H. KEHOE¹

Fellow, A. I. E. E.

Synopsis.—The New York 60-cycle system is operating with connections giving parallel paths between generating units only at the load. High values of reactance result for synchronizing circuits between the several generating units, but the usual values are present in the main energy channels between generators and load. Connections are contrasted with two common types of metropolitan power systems; i. e., the “close linked” and “loose linked” systems, and are shown supplemental to multiple-feed network distribution, as the principle of using separate multiple feeds from independent generators connected in parallel only at the load extends the network

distribution system to the generating stations. In completely networked distribution, the 120/208-volt mains acting as a short-circuit-proof bus, supply the only synchronizing paths between generators. Substation busses serving radial load are substituted where complete networks do not exist. Calculations, tests, and operating experience indicate synchronizing power sufficient to give stability to all elements of the system not directly affected by a fault. Some advantages derived are: Increased reliability of generating sources, lower interrupting duties on circuit breakers, and reduction in service voltage disturbance.

CONNECTIONS FOR IMPROVED SYSTEM BEHAVIOR

THE New York City 60-cycle power system is now operating with an arrangement of connection which gives paralleling paths between generating units only at the load. Each generator while in service on this system is described as being “synchronized at the load.” This term refers to the conditions under which each unit is maintained in synchronism, but it does not refer necessarily to the initial synchronizing

fundamentally affect the normal power distributing characteristics of the system, it does improve system behavior during abnormal conditions in several ways which are discussed in this and in companion papers.²

TYPICAL POWER SYSTEM ARRANGEMENTS

Ever since d-c. machines were first operated in parallel, or following this when individual drive alternators were first synchronized, the usual arrangement has been to provide for paralleling as near to the sources of power as possible. For a number of years, machine capacities and system reliability have required some means of obtaining increased reactance values to limit fault currents, and many large station busses have been broken up into sections by inserting current-limiting reactors. Generator leads supplying the bus and feeders from the bus in some cases have been similarly equipped. Such busses usually take the form of a closed loop or ring and are composed of a number of sections, each connected to its adjacent sections through reactances. Another scheme in use is the star arrangement, in which each individual bus section is connected through a reactor to one common bus or star point. Since the amount of reactance as well as its location in the circuit can easily be varied, many different plans of bus layout are in use. In general, however, it has become standard practise to parallel generators in a generating station as close to the source as possible by using some plan of either the “ring” or “star” bus arrangement.

Whenever systems are supplied from more than one generating station, it is customary to use either tie feeders between stations to provide an extension of the paralleling bus, or the system is divided into districts which are normally tied together with relatively low-capacity ties between each district to maintain the system in synchronism as an aid to operation under

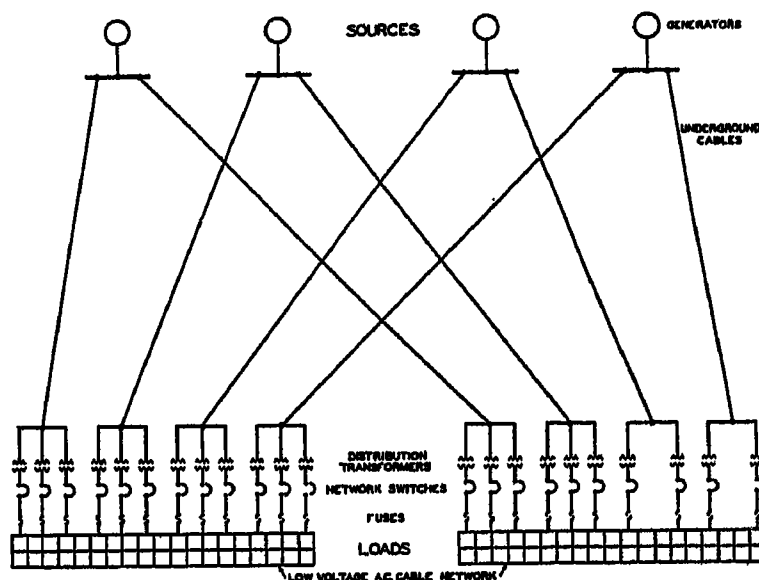


FIG. 1—SCHEMATIC CONNECTIONS FOR SYSTEM SYNCHRONIZED AT THE LOAD

of one generator with the rest of the system. Fig. 1 shows a simplified diagram of the arrangement. Such a scheme of connections gives high reactance values for the synchronizing power circuits between the several generating units in comparison to the values which are in general use with generators also synchronized at the station bus. Nevertheless, the main energy channels between generators and the load have reactances, in respect to normal capacity, of the same order as those usually experienced with metropolitan underground cable systems. Thus, while this arrangement does not

1. Electrical Engineer, The United Electric Light and Power Co., New York, N. Y.

2. *Calculations of System Performance*, by S. B. Griseom.
System Tests and Operating Connections, by H. R. Searing and G. R. Milne.

normal conditions. With the first mentioned arrangement (Fig. 2), that is, with tie feeders between generating stations, the capacity in several stations is used to supply a wide area. Therefore, it is essential that synchronism be maintained not only between all units in one station but also between all stations. This

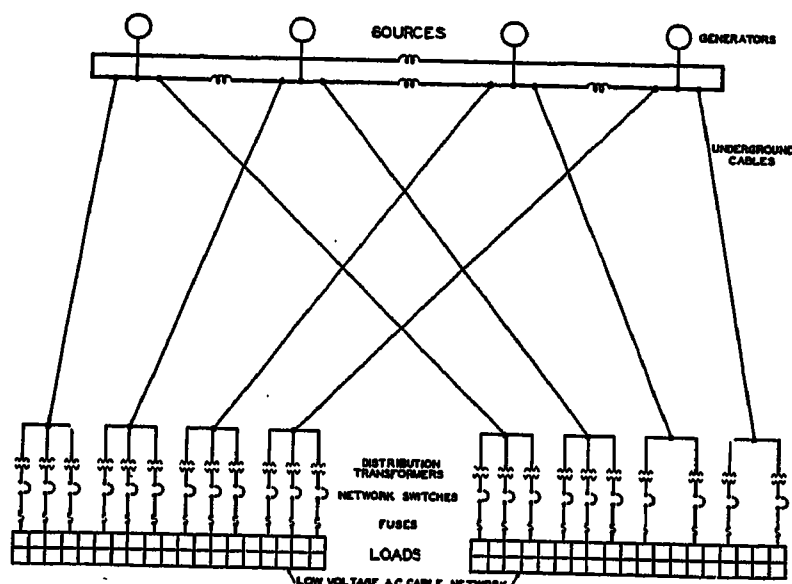


FIG. 2—SCHEMATIC CONNECTIONS CLOSE LINKED SYSTEM

has been designated as the close linked system. With the district arrangement (Fig. 3), or loose linked system, the load is definitely allocated to one adjacent station, wherein it is not essential that it should be maintained in synchronism with the remaining parts of the system. Assuming that the low-capacity ties will open properly on a major fault, this station will operate as an independent unit, alone supplying its particular district.

CHARACTERISTICS OF "CLOSE LINKED" AND "LOOSE LINKED" SYSTEMS

The close linked system requires high rupturing capacity circuit breakers, with increasing rupturing duty as the capacity of the system is increased. The fault protection is complicated, and positive back-up protection is difficult to obtain in case the primary protection fails. During system faults, service voltages are subject to excessive drops due to concentrations of current at the fault. Finally, the entire system service is at stake in case of a series of major faults.

On the other hand, the loose linked system by subdivision of the load, eliminates the likelihood of an entire system shutdown, but it does increase the probability of interruptions to each district. In addition, each station must have some efficient units if economical results are to be obtained. This system, except at district border fringes, cannot obtain the economies and reliability from diversity of a multiplicity of sources of supply. In other words, the loose linked scheme postulates that a power system can become so large that it is either economical, or imperative, to divide it into a number of separate districts power systems in order to obtain reliability.

IMPROVEMENT IN RELIABILITY OF GENERATING SOURCES

Investigation of the reliability of both the above systems made it appear that a generating station bus system providing parallel synchronizing paths would result in increased reliability to either a close linked or a loose linked system, with either ring or star bus plan. However, such an arrangement increased the switch rupturing duty and the voltage disturbances on system faults. Furthermore, it did not simplify the protection problem.

In 1924, following two years' experience with the Manhattan multiple feed a-c. network system, the author proposed for maximum reliability to operate each generator in parallel with remaining generators only on the low-voltage network.³ This system uses the load points as a short-circuit-proof paralleling bus for all the units which are "synchronized at the load." In applying the principles established by experience with multiple-feed low-voltage network distribution to a group of generators multiplied only on a low-voltage network, it was assumed that if the system were stable, the following desirable conditions would result: (a) highly reliable sources of supply, since they were not affected simultaneously by faults; (b) positive back-up fault protection; (c) minimum fault current concentrations; and (d) minimum service voltage disturbances. The definite evaluation of the synchronizing power available and of the amount necessary to keep sufficient generating sources in step to supply the load under all conditions of system faults presented problems which prohibited the immediate application of such an arrangement. The detailed determinations of these values, both by calculation and test, are described in accompanying papers.

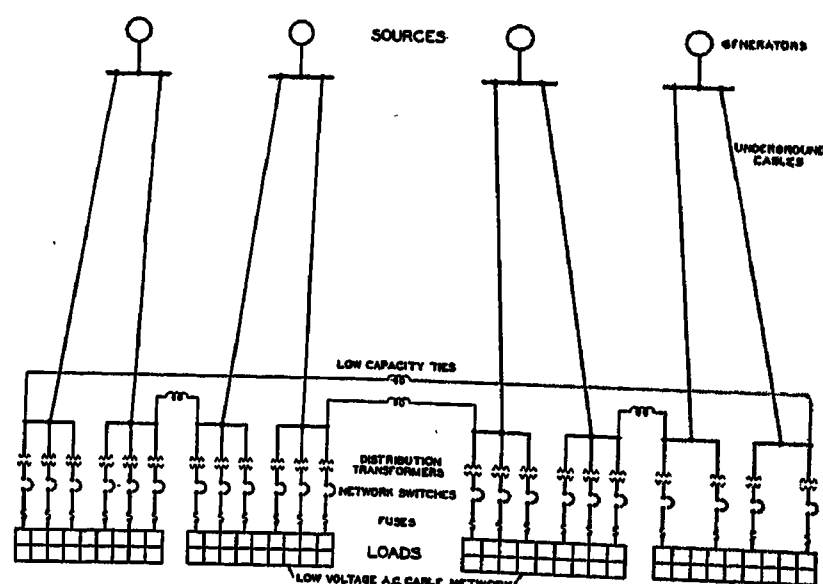


FIG. 3—SCHEMATIC CONNECTIONS LOOSE LINKED SYSTEM

The synchronizing power for the New York close linked system with this arrangement was found to be adequate. While it is less under normal conditions than that which is obtained between individual units

3. *Underground A-C. Networks*, by A. H. Kehoe, A. I. E. E. TRANS., Vol. 43, 1924, p. 848.

synchronized at the sources, yet the effective synchronizing ability at the time of a disturbance is approximately the same as with a close linked system, due to the reduced magnitude of possible faults, and the new system has high reliability due to a multiplicity of independent sources. With a loose linked system the reliability of any district would not be dependent upon the synchronizing ability of the system, but upon that of a single station. For this reason the number of possible independent sources for any district will be less than with a close linked arrangement which is considered preferable to the loose linked system if it is to be "synchronized at the load."

RELIABILITY OF SUPPLY SYNCHRONIZED AT THE LOAD

The assurance of reliability of system supply for any one fault is secured by the following considerations: Sufficient generating sources are "synchronized at the load" on a system having ample synchronizing power between the units to produce stable operation between all sources for any single fault regardless of its location, provided the fault is eliminated promptly by protective equipment. So long as enough such independent sources are in service to maintain the load, the loss of the reserve part of the capacity will not result in an interruption, since the remaining capacity is not jeopardized by this loss. The ability of a low-voltage network to eliminate its own faults⁴ will provide positive back-up protection even though a reasonable percentage of subsequent failures of protective equipment do not eliminate the original fault. If a system has radial service supplied from a substation, the low-voltage bus, such as a 4-kv. substation bus, will be the last common load point and must be used for synchronizing at the load. In this case, protective devices are relied upon for secondary protection, as there is usually a number of protective devices in series backing up each other for a major fault. In the extreme condition, a fault which is not eliminated because the protective equipment failed will cause an interruption only to the substation where such failure occurs.

SYSTEM RESULTS SYNCHRONIZED AT THE LOAD

With a system synchronized at the load, the current and load division between feeders may be affected somewhat except for peak conditions, when results should be the same. The magnitude of this effect, however, does not make it of major consideration. Similarly, in order to give the system the reliability obtained by diversity of supplies from a number of independent

sources, the load from any generator (or bus section) should scatter to as many different load centers as possible. If this is carried to extremes, the mean length of feeder will be increased unnecessarily. It is pointed out that all units do not have to feed each and every load point, and in the New York case we did not experience any increase in feeder lengths. It should also be noted that additional capacity can be supplied at lower installation costs because of smaller capacity required for electrical connections.

The arrangement makes the maximum short-circuit currents much less than are experienced on a system having a number of generators concentrated on a single bus. Furthermore, additions to system capacity do not increase the switch rupturing duty beyond the amount required by the first installation as long as the same generating capacity is maintained on existing sections.

Since the magnitude of fault currents is materially reduced and since currents from all other units must feed through the load into the fault, the resultant voltage disturbances due to system faults are materially reduced. System service voltages during major faults approximating 60 per cent to 90 per cent of normal are to be expected instead of 20 per cent to 50 per cent of normal.

CONCLUSIONS

With ample synchronizing ability inherent in the system to give stability to a number of independent power sources, whether located in one or several different generating stations, generators synchronized at the load can be connected by supply feeders to a number of load points, thus making it impossible for one fault to affect all of the generating capacity; hence, if sufficient reserve capacity is in operation, the loss caused by a single fault cannot affect the reliability. By this method, reliability of supply depends upon having immediately available sufficient spare capacity in operation to compensate for a maximum number of possible major faults which are reasonably likely to occur in the interval required to get spare capacity in operation.

ACKNOWLEDGMENTS

Acknowledgment is made to those engineers who between 1924 and 1928 have encouraged the development of the arrangement by stating that in their judgment the synchronizing ability would be ample with the 60-cycle New York City system. In particular, credit for bringing this system into operation is due to the Westinghouse engineering staff for its mathematical investigations and conclusions which were proved by test to be highly accurate.

4. *Underground A.-C. Network*, by A. H. Kehoe. A. I. E. E. TRANS., 1924. Vol. 43, p. 845. Also, *Extinction of an A.-C. Arc*, by J. Slepian, A. I. E. E. TRANS., 1928, Vol. 47, p. 1404, and *Theory of the Deion Circuit Breaker*, by J. Slepian, A. I. E. E. TRANS., 1929, Vol. 48, p. 523.

“Synchronized at the Load”—II

Calculations of System Performance

BY S. B. GRISCOM¹

Associate, A. I. E. E.

Synopsis.—This paper describes the results of calculations made for operating the Hell Gate and Sherman Creek generating stations of the United Electric Light and Power Company synchronized at the load.

After reducing the numerous branches of the system to a simpler equivalent, calculations were made on the operation of an isolated section. These calculations indicated ample static stability and transient stability under fault conditions representing the maximum which might normally be expected.

Other calculations were made indicating that the entire system,

with synchronizing paths completed through the substation low-voltage busses would likewise meet the required stability conditions.

Tentative system design factors, based on the calculations and experience to date, are suggested as a guide to system planning.

This paper shows a practical application of the theories and principles developed in the studies of transmission stability. In the present case a somewhat different object was in view inasmuch as it was desired to substantiate ideas as to the feasibility of the plan of synchronizing at the load, rather than to obtain numerical limits.

* * * * *

INTRODUCTION

IN general, the principal reason for synchronizing generators at the load is that it gives promise of increasing the reliability of power supply from the generating sources. Having as a background the many papers and technical articles on stability written recently, there is a tendency to associate stability and reliability of service. The subjects are related, to the extent that a system which is capable of reliable and continuous service necessarily possesses stability to a high degree. However, with the usually understood meaning of stability, it is entirely possible to have a stable system which may not be capable of service reliability of a high order.

An example will be used to bring out the conceptions of the term “stability” and “reliability” as used in this paper. Assume that a power system is composed of only one generating station and that all of the generators in the station are connected to one bus. Load is distributed from this bus by means of feeders connected to it through reactors of conventional value, as three or five per cent. This system would be considered stable, with generator and excitation characteristics as are in common use. However, the system might not be considered reliable because it has a vulnerable spot—the single generator bus. Major trouble on the bus, or on any part of the equipment connected to it could result in a complete system outage. Thus, the system is stable but not reliable. If the bus is divided into a number of parts and the sections thus formed are connected by reactors, the combination would be regarded as having a higher order of reliability than the system with a single straight bus. Similarly, if there are two stations, with connecting ties, the over-all reliability is considered as still greater. It will thus be noticed that the insertion of reactance

between units of a system has improved the reliability. What has happened to the stability? On a long distance transmission system stability is measured in terms of the ability of the generators to remain in step with the receiving end of the system, comprising the load and local generating stations. On a more compact system in which the load is fed through multiple paths from different generating units, the requirements of stability are met as long as the generators remain in step with one another. Therefore, the insertion of reactance not normally carrying current between generators does not affect the static stability of the system as a whole, but decreases the static stability of the individual generating units somewhat. The transient stability (relating to operation during dis-

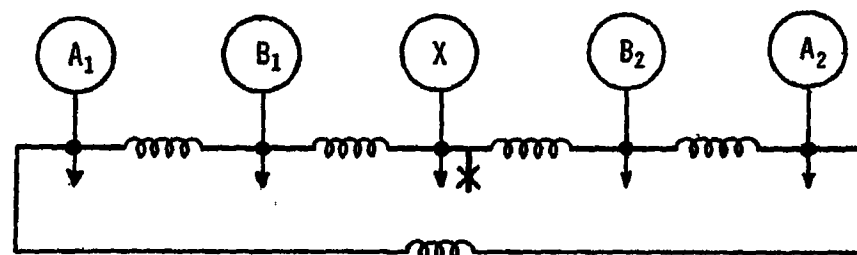


FIG. 1—RING BUS CONNECTION. GENERATOR REACTANCE 12 PER CENT

turbances such as short circuits) may be increased or decreased, depending upon the relations between synchronizing power and fault conditions for the two cases.

An example will be given, showing not only how increased reactance between generator busses affects transient stability, but also that other effects, difficult to evaluate, must be considered in determining the reliability. Fig. 1 shows the assumed layout. The generators are 100,000 kv-a., 12 per cent reactance each, while the connecting reactors may have values of 5 per cent, 15 per cent, and 40 per cent. Due to the symmetrical layout, it is possible to show the effect of a three-phase short circuit on one bus considering two machines only, as A and B, the short circuited machine going out of step and not affecting the others. Figs. 2,

1. General Engineer, Westinghouse Elec. and Mfg. Co., East Pittsburgh, Pa.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

3, and 4 show the voltage and angular relations for reactor reactances of 5 per cent, 15 per cent, and 40 per cent respectively. It should be noted that if the angular oscillation between machines is regarded as a measure of stability, the higher values of reactance afford less stability, but if voltage is also considered, the advantage is definitely on the side of higher reactances. Fig. 5 still further brings out the improvement obtained by the use of high reactance between generating units. The analysis was on the basis of an

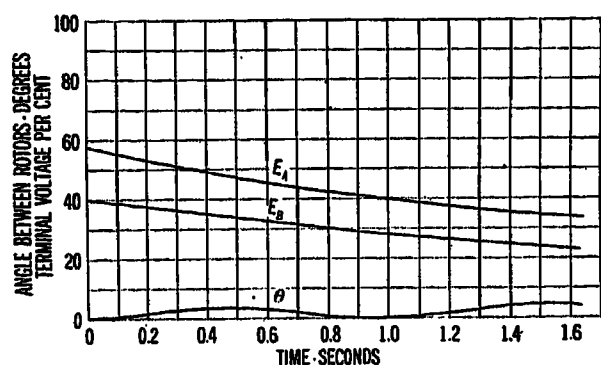


FIG. 2—VOLTAGE AND ANGULAR RELATIONS FOR REACTOR REACTANCE 5 PER CENT

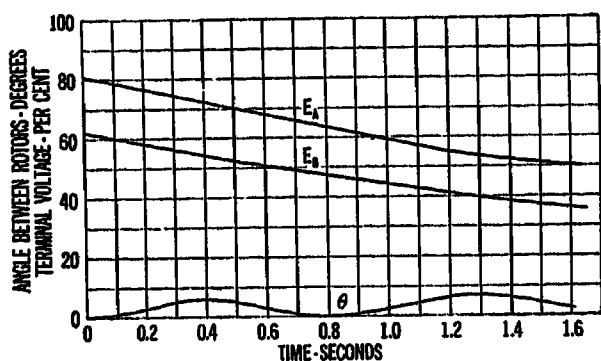


FIG. 3—VOLTAGE AND ANGULAR RELATIONS FOR REACTOR REACTANCE 15 PER CENT

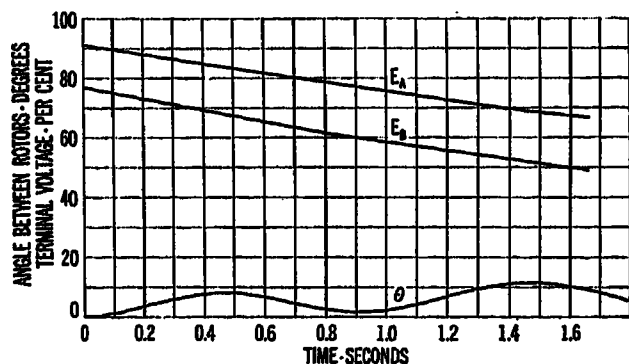


FIG. 4—VOLTAGE AND ANGULAR RELATIONS FOR REACTOR REACTANCE 40 PER CENT

isolated system, and as the short circuit deprives the generators of considerable load, the whole system speeds up. The average frequency of the machines for the three cases is shown by Fig. 5 and it will be noted that the higher the reactance between generating units, the less the over-speed. With a single station as indicated, not interconnected with other stations or other systems, this tendency to over-speed is not so serious, but if connected, there is very much more likelihood of pulling out of step from the other stations when the lower values of reactance are used. Thus, judged by angular shifts,

a system with generating units tied through low reactance has greater stability than one where high reactances are used, but may have far less reliability and be subject to much greater voltage disturbances.

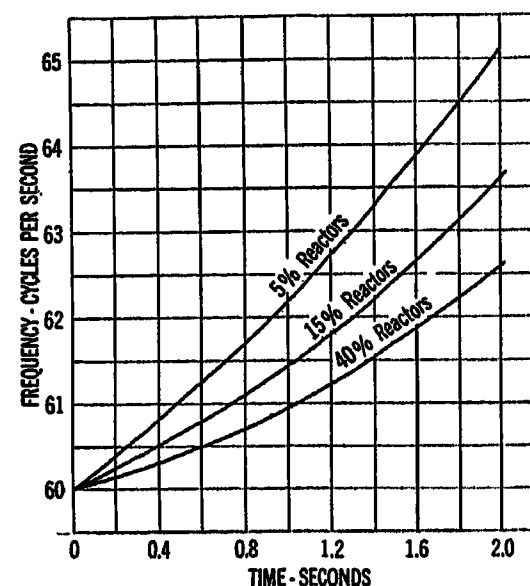


FIG. 5—VARIATION OF NET SYSTEM FREQUENCY WITH THREE PHASE SHORT CIRCUIT ON ONE BUS OF A RING BUS SYSTEM

The analysis as described above omitted a number of factors which are difficult to evaluate but which are none the less important. For instance, it was assumed that all of the generators were similar both as to rating, reactance, inertia, and initial loadings and that the governors did not operate; in other words, that everything was symmetrical. Lack of symmetry will cause more difficulty where the generators are tied through low reactance.

STABILITY REQUIREMENTS FOR SATISFACTORY OPERATION WHEN SYNCHRONIZED AT THE LOAD

The fundamental plan of synchronizing at the load is described in a companion paper by Mr. A. H. Kehoe. This plan gives a redistribution of reactance on the system so that the reactance between machines and in

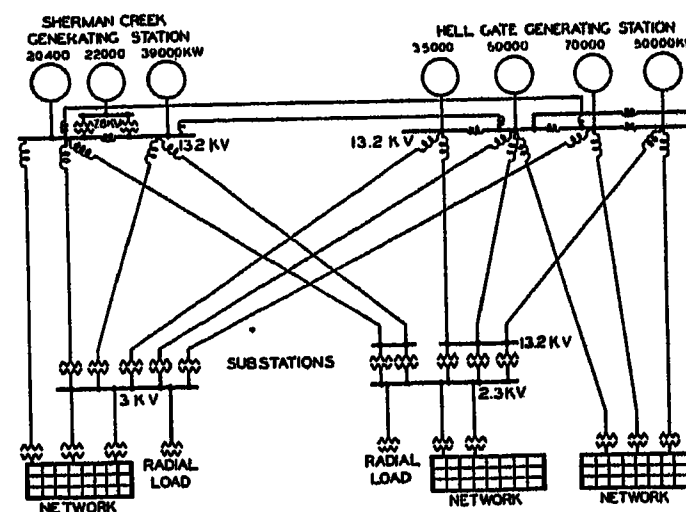


FIG. 6—SYNCHRONIZED AT GENERATING STATION BUSES

series with faults is considerably increased. Fig. 6 illustrates in a schematic manner the connections which have been in use in the 60-cycle parts of the generating stations of the United Electric Light and

Power Company and in the system external to them. The generating busses were tied to one another very closely, inside the stations by bus-tie reactors and outside of the stations by cables at generator voltage. The stations themselves were directly tied together by high-voltage cables. Fig. 7 shows the same equipment but synchronized at the load with the reactance between generating units considerably increased by the omission of the bus-tie reactors and inter-station ties, and by splitting the substation high-tension busses. This scheme of connection is only partly equivalent from the stability point of view to a ring bus scheme in which high-reactance reactors are used between busses since the actual ties between units consist of a large number of branches in parallel and because each generator tends to have symmetrical ties with each other generator. In fact, from this point of view, the arrangement is more nearly like the synchronizing bus or Staat connection, but does not have any points where large amounts of energy are concentrated. The stability and reliability of the synchronized at the load

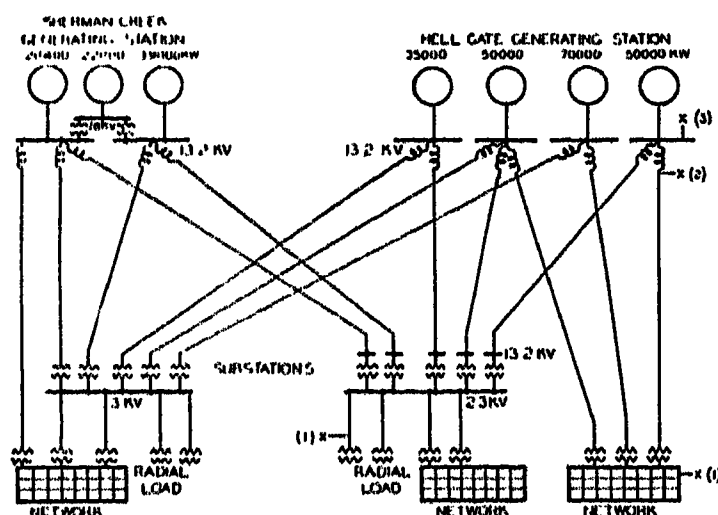


FIG. 7—SYNCHRONIZED AT THE LOAD

arrangement compared to the previous arrangement depends upon the relative amount of change in reactance in series with faults and between generating units. The calculated performance when synchronized at the load is described in this paper, while the test and operating results are described in the companion paper by Messrs. Searing and Milne.

The rigid requirements for power supply in a metropolitan area necessitate a system which has static stability under all conditions of operation, and transient stability under all conditions of operation with the exception that in some cases a disturbance may result in loss of a generating unit, and this is permissible, but it is required that the remaining units maintain synchronism with one another. In addition to possessing the necessary stability, there must be no undesirable hunting between generating units. The layout of the system is such that if stability can be obtained, the requisite reliability of service will automatically be obtained, vulnerable points having been largely eliminated.

By static stability is meant that the generating units shall be capable of carrying the required load

under normal conditions without loss of synchronism. With such a closely connected system, it appeared likely that such would be the case, and the analysis of this point was made largely as a formality.

There are three transient conditions to be considered. One condition is a fault located more or less equidistantly from each of the generating units, as (1) on Fig. 6. From the nature of the layout, it is apparent that such a fault affects all of the generators similarly and practically in proportion to the size of the machine, hence, would be almost unnoticed. Another condition is a fault on a feeder close to one generator unit, such as (2), Fig. 7. Practically, this condition resolves itself into a fault on the feeder side of a feeder reactor on one of the generating units. A fault at this location has a tendency to cause the generator nearest it to go out of step. The third transient condition is that of a short circuit on one of the generating bus sections as illustrated by (3), Fig. 7. This condition will almost invariably cause the loss of the generators connected to that bus section. However, it is required that only the remaining generators stay in synchronism with each other.

From the foregoing, it will be seen that the most important considerations from the stability point of view are that all of the generators keep in synchronism for short circuits on the feeder side of a feeder reactor, and that all of the generators except those directly involved stay in synchronism during a bus short circuit. The three-phase short circuit is the most severe, and has therefore been made the basis of study.

Methods of Analysis.

There are, in general, three ways of making an analysis for stability: calculation, laboratory tests, and field tests. It was found that the major portion of the work involved was in obtaining values of the various impedances because of the unusually large number of feeders, and since a determination of these values for the existing and proposed system of the United Electric Light and Power Company was a necessary part of the program, all of the analysis was made by calculation. Later, tests were made to give an over-all check on the derivation of system impedances, machine characteristics, and the electromechanical oscillations set up by short circuits.

The general methods of calculation have been described in several papers before the Institute and details will not be given here. In all calculations, the load was considered as a shunt admittance. This assumption was necessary because of the amount of work which otherwise would have been required, but it is probably fairly accurate for the system under consideration because of the relatively large amount of lighting load. For the static stability analysis, the synchronous reactances of the generators at the initial operating points were used. For the transient analyses, the transient reactances of the generators were used. The effect of variations in the cross flux was not considered.

Decrements of main field flux, and the general method of calculation were about as given in the paper *Studies of Transmission Stability*.²

The studies which were made were divided into two groups, one being on a portion of the system which, in addition to lending itself readily to tests, also is of the type representing what appears to be the tendency in the growth of the system. This part of the system was that which was fed mainly by the 120-208-volt a-c. network system. Other analyses were made covering the entire system as it was expected to be when the plan was first placed in operation. The discussion will therefore be divided between the analyses of one generating unit split from the system and operating on the networks, and the entire system with generating units separated at the generating station and synchronizing ties through the low-voltage substation busses.

PARTIAL SYSTEM ANALYSIS

Reduction of Network. The part of the system analyzed is shown by Fig. 2 in the companion paper *System Tests and Operating Connections, Synchronized at the Load*. In this figure, each small square represents a networked area and consists of hundreds of branches. Due to the extremely large amount of work which would be required, it was not considered feasible to solve each of the networked areas. However, the general structures of all of the networks is about the same. Transformers step down to the network from the high-voltage cables and the total capacity of these transformers bears some relation to the amount of load to be served. The load is located partly along the secondary mains in the streets. The density of load, of course, affects the spacing of the step-down transformers, but considering that each customer must be supplied with energy with a reasonable voltage regulation, it is evident that the total impedance from a high-voltage feeder to the ultimate load will tend to average to some definite percentage value with the load as a base. This refers to the impedance from the high-voltage cables to the network load. From the stability point of view, it is necessary to find the effective impedance through the network, from one generating source to another, it being this value which affects the flow of synchronizing power. To secure reliability in network operation it has been customary to feed a given area from as many independent points as possible so that if the supply from one source is interrupted, the load can be carried from the other sources. The load distribution from the various sources is carefully divided so that each source carries part of the load of practically every section of the area. For this reason, it is logical that the impedance to the flow of synchronizing power should also work out to be a function of the transformer capacity connected to the various sources.

2. Evans and Wagner, A. I. E. E. TRANS., Vol. 45, 1926, pp. 51-94.

From the stability point of view, it is usually desired to analyze for the synchronizing power of one generating unit referred to all of the remaining generators as a unit. This requirement suggests obtaining, if possible, a figure of coupling impedance from each source to a fictitious central point, in terms of the transformer capacity connected to the source, or in other words, a star form of representation.

Fig. 8 shows the appearance of typical network. The lines represent 120-208-volt secondary mains and are interconnected wherever they are shown as crossing on the diagram. The network is fed from several different sources, some at 13,200 volts, and others at 3000 volts. Feed-in points are indicated by the trans-

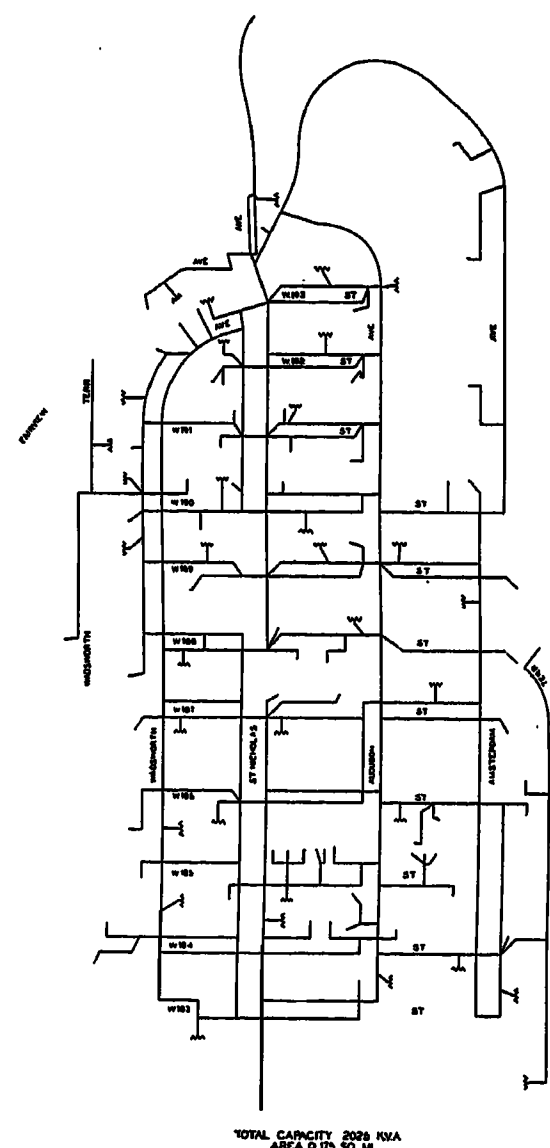


FIG. 8—FORT GEORGE NETWORK

former symbol. The high-voltage cables are not shown on the diagram. Considering, however, that each high-voltage cable will supply a number of step-down transformers and that the high-voltage cables may have the same substation bus as a source, the number of independent sources is brought down to from three to six. A typical three-phase and a typical one-phase network were solved and the results considered to be generally applicable to the other networks, according to the connected transformer capacity.

A scale was made to convert distances of the map to reactances, and the reactance diagram of the network was made. The reactances of the transformers were then added at the feed-in points. The network

was then set up on a d-c. calculating board, bussing on the calculating board all of those feed-in points which were supplied from separate and distinct sources. Thus, the entire network would be involved in the calculating board set-up, but there would be only as many terminals to be considered as there were separate sources. Measurements can now be made on the calculating board which will permit reducing the complicated network to the minimum number of branches. In general, any network can be reduced to a mesh in which there is

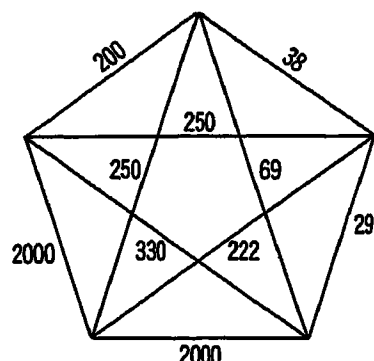


FIG. 9—EQUIVALENT MESH FOR NETWORK. VALUES GIVEN ARE OHMS AT 13,250 VOLTS

a branch connecting each terminal point with each other terminal point, and this form of representation will give the smallest number of branches that can be used and still represent the original network *exactly*. Fig. 9 shows such an equivalent mesh for the network of Fig. 8. The values of the branches between the feed-in points are obtained as follows: On the short circuit board, connect all of the feed-in point busses but one to the negative bus, as indicated in Fig. 10, and supply potential from the positive bus to the re-

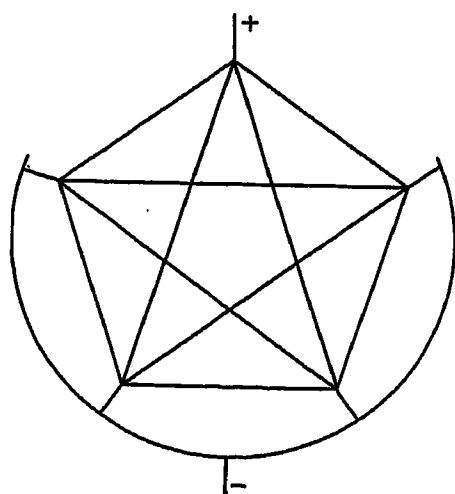


FIG. 10—METHOD OF OBTAINING EQUIVALENT MESH

maining feed-in points. An inspection of Fig. 10 will show that the current which flows from the positive to the negative bus through the network (or in the equivalent mesh which is to represent it) divides between the four feed-in points in proportion to the admittance of the branch from the positive feed-in point to the negative bus; each of the four other feed-in points being at the same potential, no current can flow in the branches connecting them. The admittance from the single feed-in point to each of the other feed-in

points may thus be obtained directly from the current reading. If this process is repeated until each feed-in point has been used singly with the others paralleled, two determinations for the value of each branch of the equivalent mesh will have been obtained, thus furnishing a check. The mesh thus obtained is exactly equivalent to the original network.

In order to apply the results obtained from the analysis of two networks to the solution of all of the networks, it is necessary to put the results in terms of the impedance from source to central point, according to connected transformer capacity, as explained previously. There is no exact conversion between the mesh and star forms of network representations for the reason that the mesh is the general form and the star a restricted form which is only applicable when there are certain relations between the branches of the mesh. An approximate formula for the conversion from mesh

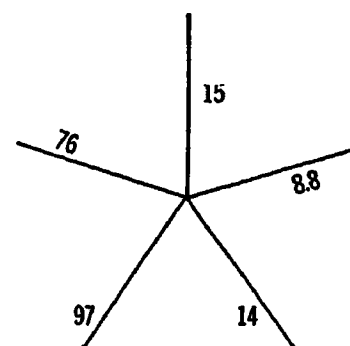


FIG. 11—APPROXIMATE EQUIVALENT STAR

to star form which has been found to give good results is as follows:

$$Z_1 = \frac{1}{Y_1} - \frac{1}{\frac{(n+2)}{n} (Y_2 + Y_3 + \dots + Y_n)}$$

$$Z_2 = \frac{1}{Y_2} - \frac{1}{\frac{(n+2)}{n} (Y_1 + Y_3 + \dots + Y_n)}$$

Where Z_1 = impedance of branch from terminal (1) to star point.

Z_2 = impedance of branch from terminal (2) to star point, etc.

Y_1 = Total admittance from terminal (1) to all other terminals in parallel.

Y_2 = Total admittance from terminal (2) to all other terminals in parallel, etc.

n = Number of terminals.

Fig. 11 shows the approximately equivalent star obtained in accordance with the above formulas.

This conversion formula from mesh to star form is empirical and should not be used where it is known that the mesh can be converted to an exactly equivalent star as for instance, where the mesh form has been derived from the star form. Also, there is an exact conversion between mesh and star forms where there are only three terminal points and this conversion should be used in such a case.

A three-phase and a one-phase network were solved in this manner, and due to the fact that the feeds were at 13,200- and 3000-volts, with transformers of different reactance, the results were somewhat different as shown below. The results are expressed as per cent reactance from the high-voltage cable source to the fictitious star point and based on the combined kv-a. ratings of the step-down transformers.

13,200 volts 3 phase.....	11 per cent
3,000 volts 3 phase.....	7 per cent
13,200 volts 1 phase.....	33 per cent
3,000 volts 1 phase.....	15 per cent

Tests made on the Times Square network as described in a companion paper gave an average impedance of 5.1 per cent and an average reactance of 4.3 per cent not including transformer reactance. This was a 3000-volt, three-phase network, and, adding the transformer reactance of 2.7 per cent gives 7 per cent reactance from high-voltage cable to star point.

After having thus obtained the reactance of the network elements, values were substituted for the small

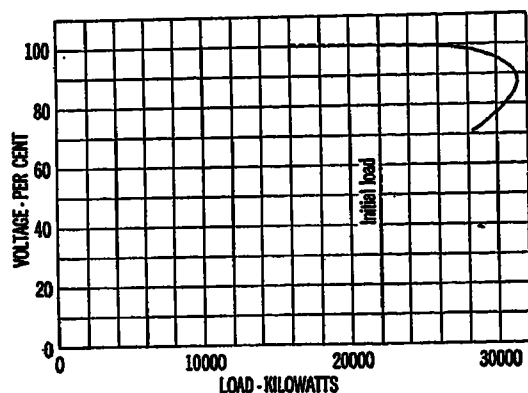


FIG. 12—VOLTAGE-POWER CHARACTERISTIC, INDICATING STATIC STABILITY

squares of Fig. 2 of *System Tests and Operating Connections*, (Part III of this symposium), in accordance with the transformer capacity connected to the various cables. The effective reactance between the generator to be tested and the remainder of the system, through the networks was found in this manner. Resistance components were then added to the reactances according to what was considered to be the probable ratio of resistance to reactance. Admittances were placed along the connecting impedance between the two generating sources in proportion to the probable electrical distances of these loads from the sources. This gave a static network to which it is only necessary to add the generator reactances to proceed with the analysis.

Static Stability. The synchronous reactance of the generator under test and the remainder of the generators grouped were added at the proper ends of the connecting network, and, with the internal voltages determined in accordance with the initial loadings, completed the data necessary for obtaining a static power-angle diagram. Points were picked off of this characteristic and the

generator terminal voltage computed to give the points of the voltage-power characteristic of Fig. 12, this form being more readily interpreted. It will be noted that with an initial load of 22,000-kw. at 100 per cent voltage the static stability analysis indicates that with fixed field excitation, a load of 31,500 kw. could be carried before pullout takes place at 88 per cent voltage. This, of course, does not mean that a higher load than 31,400 kw. could not be carried, but merely represents the approximate margin for a given initial load and corresponding field excitation. This analysis indicates that there

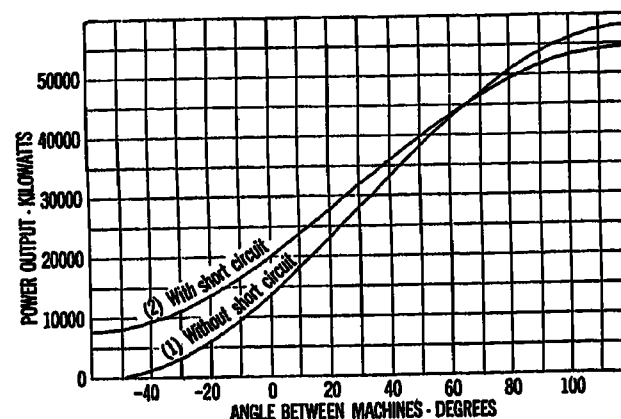


FIG. 13—CALCULATED TRANSIENT POWER ANGLE DIAGRAMS

is ample static stability without the use of automatic voltage regulators.

There was some speculation as to the possibility of hunting, but this factor cannot readily be examined in advance. It was felt, however, that no hunting would occur, and this was found to be the case when tested.

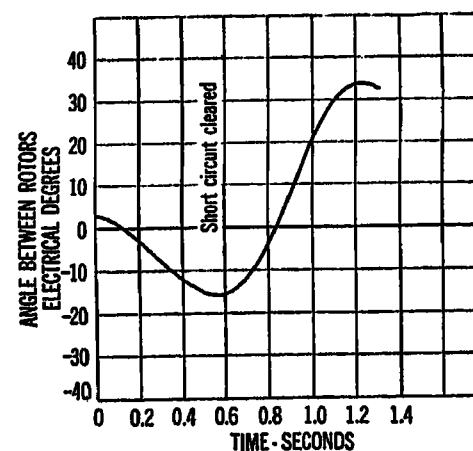


FIG. 14—CALCULATED ANGULAR VARIATION IN GENERATOR ROTOR POSITION

Transient Stability. The first analysis of transient stability was made for the condition of a fault on a feeder 8000 ft. from the station. Transient power-angle diagrams were obtained by combining the transient reactances of the generators in series with the static network previously obtained, giving the curves of Fig. 13. Curve "1" shows the conditions for normal operation and curve "2" shows the conditions with the feeder fault. The term "transient power-angle diagram" is here used to refer to the variation in power output of the generator as a function of angle, when the time required to move

from one point to another is very short, or in other words, that the internal voltages of the generators are the same as for initial conditions. In making the step-by-step calculations, the decrement of the main generator field fluxes were calculated and corrections made therefor.

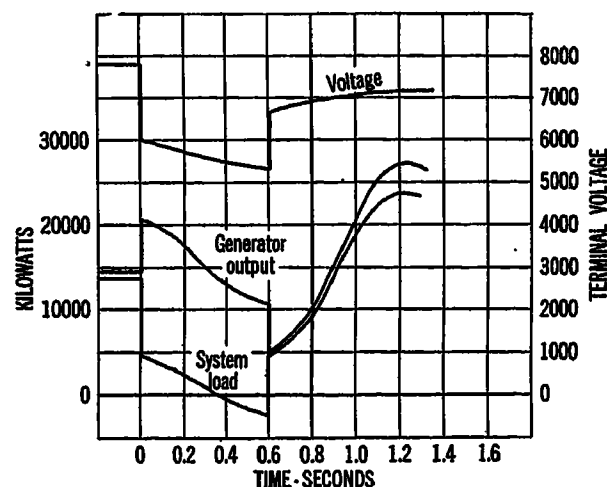


FIG. 15—CALCULATED GENERATOR VOLTAGE, GENERATOR LOAD AND SYSTEM LOAD CORRESPONDING TO FIG. 12

Fig. 14 shows the calculated variation in angular position of the rotors of the generators with a short circuit on for a period of 0.6 sec.

Fig. 15 shows the variation in generator voltage, generator load, and network load during, and for a short period following the short circuit. The network load is equal to the generator load minus the loss in the connecting network, and, in the case of the short circuit, the power lost in the short circuited cable. This figure may be compared with the results obtained on one of the tests and for convenience, these results are reproduced here in Fig. 16. It will be noted that the results show the same general characteristics and some of the differences can be explained by differences in set-up. The

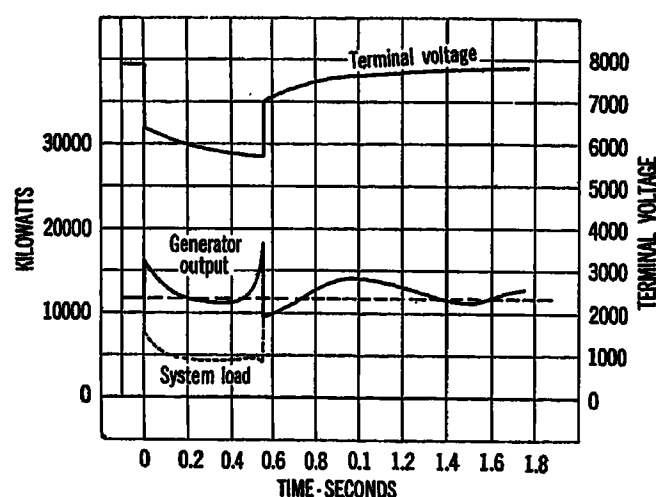


FIG. 16—TESTED CHARACTERISTICS FOR CONDITIONS SIMILAR TO THOSE OF FIGS. 12 AND 13

test length of short-circuited cable was 5000 ft. instead of the value of 8000 ft. used in the calculations, giving a smaller rise in power when the short circuit is applied. The initial load was 11,500 kw. instead of the value of 14,500 kw. used in the calculations. When the circuit breaker opened to clear the fault, there was a con-

siderable momentary power loss in the breaker which was not considered in the calculation. There is also a considerable damping torque generated by the fluxes in the generator and this and the variation of cross-flux were neglected in calculation. In general, however, the conclusions reached by tests and the calculations made prior to them were the same, that is, that with short-circuit currents of the order and duration tested, and with tie impedances as existing at the time of the test, the system would be stable under such transient conditions.

Some approximate analyses and the other tests which were made showed that a short circuit directly outside of the station would be more severe from the stability point of view, but they could likewise be handled.

Comparison of Calculated and Derived Power-Angle Diagrams. During the tests, the set-up was such that the equivalent voltage of the entire system with the exception of the generator under test was available in the same station as the tested generator, so that facilities were available for measuring the magnitude of both

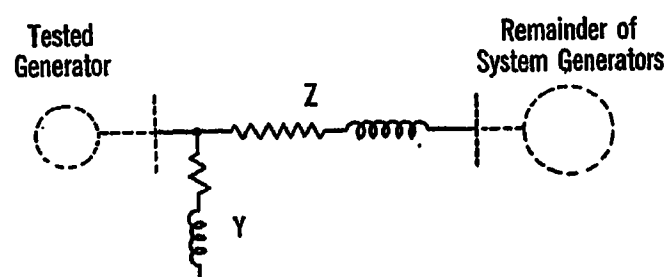


FIG. 17—APPROXIMATE NETWORK EQUIVALENT OF SYSTEM CHARACTERISTICS DURING TESTS

voltages and the phase displacement between them. In addition, oscillographic records were obtained of the variations in power and kv-a. output of the generator and power and kv-a. drawn by the fault, so that the difference gave the power output into the connecting network, from instant to instant, during and after the short circuit. These oscillographic readings were used to obtain an experimental check on the characteristics of the system between the tested generator and the remainder of the system. Fig. 17 shows a general form of static network for representing the system connections, consisting of an impedance between the machines and an admittance at the terminals of the tested generator. The admittance corresponding to the load on the remainder of the system need not be considered because of its relative size. Therefore, considering only the branches Z and Y , the following relations apply:

$$E_s = E_r + Z I_r$$

$$I_s = I_r + Y E_s$$

hence:

$$E_s = E_r + Z (I_s - Y E_s)$$

The vector values of E_s , E_r , and I_r are known at various

time intervals; hence, by setting up simultaneous equations in pairs, determinations of Z and Y may be made. The following independent determinations were obtained:

Z Ohms at 8000 volts	Y Mhos at 8000 volts
0.199 + j 1.150	0.354 - j 0.073
0.204 + j 1.312	0.334 - j 0.158
0.062 + j 1.118	0.271 - j 0.049
0.448 + j 0.997	0.435 - j 0.215
Average 0.228 + j 1.144	0.349 - j 0.124

These values may be expressed in terms of the generator rating of 25,900 kv-a., and on this basis the impedance becomes 9 per cent resistance and 46 per cent reactance and the admittance becomes the equivalent of 22,000 kv-a. at 94 per cent power-factor lagging (at normal voltage). So far as known, the above represents the first experimental determination of transient load characteristics, expressed in the static network form.

When the transient reactances of the generators were added to the ends of the network thus obtained, the

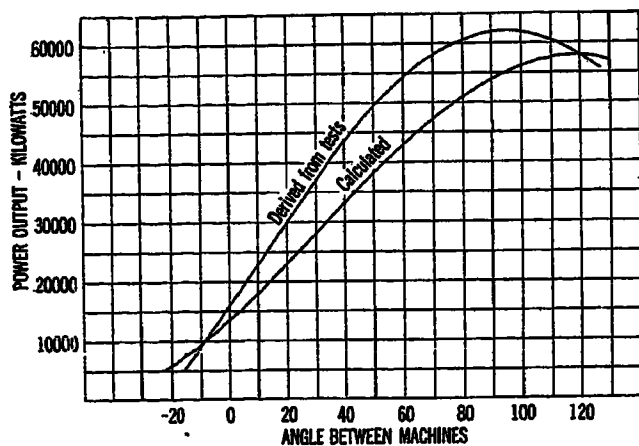


FIG. 18—CALCULATED AND DERIVED POWER ANGLE DIAGRAMS

total impedance to the flow of synchronizing power was found to be 60 per cent on the generator rating. Because of the shunt load, however, the maximum point on the transient power-angle diagram is considerably in excess of the value corresponding to 60 per cent impedance. Fig. 18 shows the power-angle diagram as derived in the above manner, and the calculated power-angle diagram of Fig. 13 is added for comparison.

Fig. 19 gives a comparison of the measured and derived angle time diagrams for test No. 10. The measured curve was obtained from the oscillographic measurements with a small correction for the internal angle of the generator, while the derived curve was obtained from the derived system characteristics, and the measured variations in power output. Considering the manner in which the determinations are interleaved, this figure indicates a fairly good over-all check.

Fig. 20 shows the saturation curve of the generator tested. It is interesting to note that the generator had a short-circuit ratio of 0.76 and despite the fact that

there was an instantaneous symmetrical three-phase short circuit of about $2\frac{1}{2}$ times full load on the generator for 1.8 sec., and a relatively weak tie to the remainder of the system, the generator remained in step.

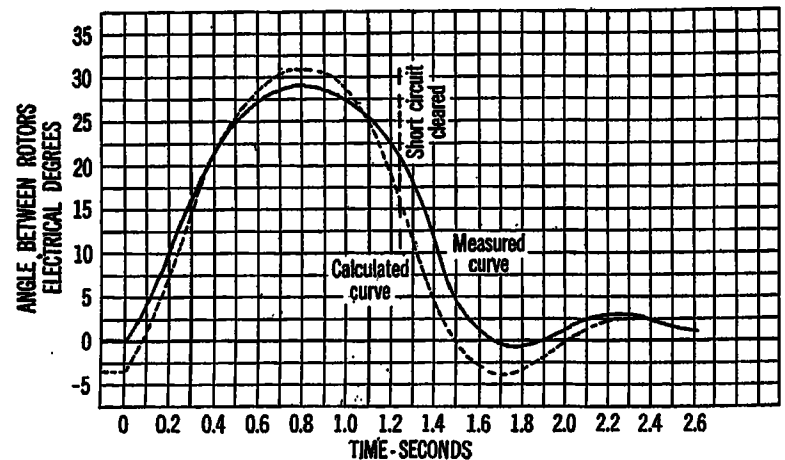


FIG. 19—MEASURED AND DERIVED ANGULAR SWINGS DURING TEST No. 10

The initial load was approximately 60 per cent of rated load, at rated power factor and no automatic voltage regulators were in use. These figures show quite clearly that *high short-circuit ratios are not required of turbo generators for power supply in relatively closely connected systems.*

ENTIRE SYSTEM

In analyzing the entire generating system of the United Electric Light and Power Company, there are

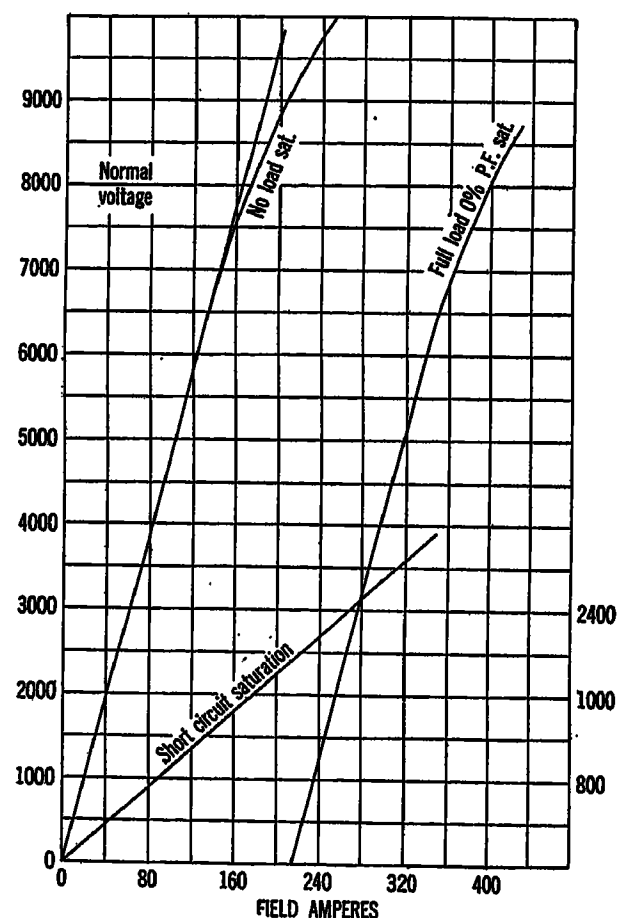


FIG. 20—SATURATION CURVES OF TESTED GENERATOR

two transient stability requirements to be met as well as the static stability requirement. It must be capable of withstanding a three-phase short circuit on one of the generating busses without the other generators losing

synchronism, and it must be able to withstand feeder short circuits. It was not considered necessary to repeat the analysis of static stability in view of the results obtained on the portion of the system previously analyzed.

The proposed initial layout for synchronizing at the load is shown by Fig. 5 in the companion paper by Messrs. Searing and Milne and it will be noted that the synchronizing tie in this case is principally through the substations rather than through the a-c. low-voltage network.

A calculating board set-up was made as in the previous studies to obtain the equivalent mesh of the ties external to the generating stations. The reactances of the various generators were then added to the mesh, and another calculating board study made for the equivalent mesh including the internal reactances of the generators. The following table shows the per cent reactance between the internal voltage of the generators connected to each bus and the internal voltages of all other generators combined, based on the combined ratings of the generators connected to the bus in question.

Bus section	Per cent reactance
N. E.	30 per cent
S. W.	29 per cent
4	50 per cent
5 and 6	50 per cent
7	50 per cent
8 and 9	52 per cent

These values indicate that the system is at present somewhat unbalanced with reference to the synchronizing power of the various generators. This is due to a temporary local condition in that the feeder capacities at Hell Gate and Sherman Creek are not in proportion to the generator capacities. This condition will gradually disappear as cable rearrangements and additions are made.

Bus Short Circuit. A solid three-phase short circuit was considered as applied to the bus section which gave the largest short-circuit current. Under this condition, the generators operating on this bus section immediately lose all of their load, and over-speed. The resultant effect on the other generating bus sections depends upon how much dissymmetry there is in the layout. With an entirely symmetrical layout, the other generators would tend to speed up in unison with no tendency to lose synchronism with each other. In order to simplify the analysis, the results were calculated on the basis of reducing the system to two equivalent generating groups. One of these groups included those generators on the bus section having the maximum differences from the others, while the remaining generators were grouped together.

Fig. 21 shows the results obtained. It will be noted that the angular oscillation between the generating groups is very small, and that the drop in voltage is

quite nominal considering the character of the fault condition. This analysis indicates that the proposed scheme can operate and furnish stable and reliable service with a solid three-phase short circuit on one bus, provided there is enough generating capacity in reserve, and provided that the bus section is isolated in a reasonable time by the opening of feeder switches.

Feeder Short Circuits. A transient stability analysis was next made with a short circuit on the feeder side of a feeder reactor, the reactance of which was such as to

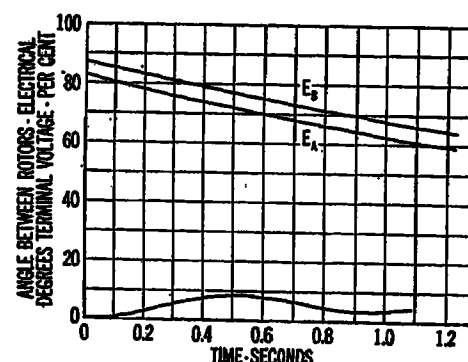


FIG. 21—EFFECT OF BUS SHORT CIRCUIT WITH ENTIRE SYSTEM SYNCHRONIZED AT THE LOAD

produce a short-circuit current of three times the full-load current of the generators connected to the bus. To facilitate calculations, the generators were grouped so that those on the bus having the short-circuited feeder constituted one group, and all other generators the other group. The results of this analysis are shown by Fig. 22. It will be observed that this condition sets up a considerably larger oscillation than the bus short circuit, but that considerably less voltage disturbances are set up. This calculation indicates that short circuits up to three times the current rating of the nearest generators and having a duration up to about two sec. can be handled successfully. However, where possible, both the current magnitudes and duration should be reduced as this will constitute less hazards and give less voltage disturbance.

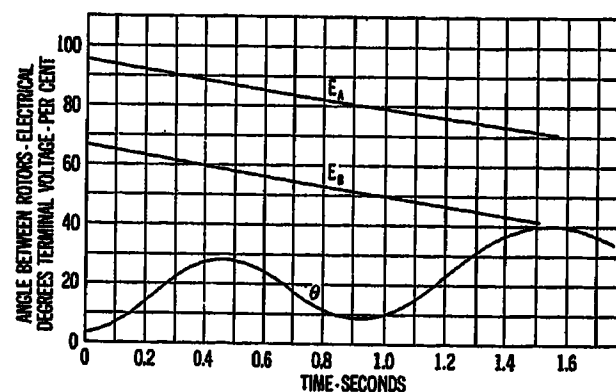


FIG. 22—EFFECT OF FEEDER SHORT CIRCUITS WITH ENTIRE SYSTEM SYNCHRONIZED AT THE LOAD

Operation of Interconnected Systems Both Synchronized at the Load. If connected systems had a common load throughout, and the interleaving of tie reactance was carried out in the same manner as can be done on the single system, the operation of two systems interconnected would be exactly the same as one system of

greater capacity. In general, however, there is a relatively small common load between various interconnected systems so that the facilities for thorough interleaving are small. It is therefore apparent that the reactance between two interconnected systems will be considerably higher on a percentage basis than the reactance between the various generators on a single system. Therefore, the synchronizing power which can be developed between two interconnected systems is much lower in proportion to the aggregate capacity of the systems than the synchronizing power available for each of the generators on a single system. However, there is another circumstance which makes it unnecessary to have low reactance between systems. The synchronizing power which is required to keep generators in step is almost directly proportional to the disturbance which tends to force them out of step. Considering a single generating bus section on a system, the magnitude of disturbance which it might receive (such as a short circuit of three times normal) is large compared to its size and a relatively high synchronizing power (or low tie reactance) is necessary. With two systems inter-connected, each of which is laid out so as to restrict short circuits to a *low value* in relation to the *entire system*, a short circuit on one cannot seriously disturb the system as a whole, and therefore the requirements for the flow of synchronizing power between the inter-connected systems is minimized.

A study was made of two large systems interconnected by ties having an aggregate capacity of 60,000 kv-a. and 30 per cent reactance. The aggregate connected generating capacities of the systems were 700,000 kv-a. and 400,000 kv-a. It was found that generating capacity carrying 100,000 kw. of load could be dropped from the smaller of the two systems without loss of synchronism. In order for this to be considered as a practical emergency condition, it would, of course, be necessary that a considerable portion of the 100,000 kw. be quickly picked up by spare capacity on the system actually losing the large unit.

No analytical study was given to the results to be expected, if the loss of a large unit was coincident with a bus short circuit, but it is quite likely that this condition could be successfully met.

Fig. 23 indicates in a schematic manner what is probably the most desirable method of interconnecting two systems, both of which are synchronized at the load. As indicated there, the tie lines are of sufficient number so that the loss of one will not seriously reduce the synchronizing power, and the tie-in points are distributed in such a manner that a large part of either system is not affected by a short circuit on one of the tie lines.

Furthermore, short circuits on one system will not produce very noticeable effects on the other system.

TENTATIVE DESIGN CONSTANTS

From the studies and tests made thus far, the following values are suggested as reasonable for system design.

Synchronizing Ability between Generators. The impedance between the internal voltage of one generating unit and the internal voltage of all other units of the same system in parallel (not including ties to other systems) should lie between 40 and 60 per cent based on the kv-a. rating of the generating unit.

Synchronizing Ability between Systems. The im-

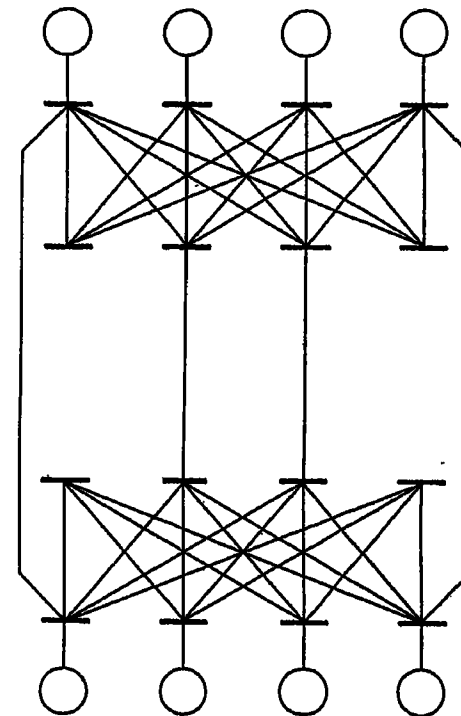


FIG. 23—SCHEMATIC DIAGRAM OF INTERCONNECTED SYSTEM, BOTH SYNCHRONIZED AT THE LOAD

pedance between two systems both of which are synchronized at the load should not exceed 200 per cent on the rating of the smaller of the two systems.

Short Circuits. The maximum instantaneous symmetrical short-circuit current on a feeder from a generating unit should not exceed $2\frac{1}{2}$ times the normal current capacity of the generating unit and should not be permitted to last longer than $1\frac{1}{2}$ sec. For simplicity this value should be obtained on the basis of a short circuit with the highest capacity feeder reactor in series with the generating unit on a three-phase short circuit. For higher values of short-circuit current the duration of short circuit must be reduced.

Circuit Breaker Capacity. With the above system proportions, the interrupting duty on a generating unit breaker will not, in general, exceed $1\frac{3}{4}$ times the generator short circuit current.

"Synchronized at the Load"—III

System Tests and Operating Connections

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Synopsis.—System test results, operating connections, and experience with the New York City system synchronized at the load are given. Data obtained by test are presented, showing the behavior of the system when generators are operated synchronized only through a low-voltage a-c. secondary network.

The adaption of this method of connections to the New York City 60-cycle system, including system layout, station and feeder re-

arrangement, and automatic recording apparatus is described.

Experience with these connections has demonstrated that stable performance of prime movers is obtained, load and wattless control is simplified, oil circuit breaker duty is reduced, and voltage fluctuation at customer's service during system disturbances is materially decreased.

* * * * *

THE New York City 60-cycle system is principally supplied by the generating stations of the United Electric Light & Power Company with interconnections to the Brooklyn Edison Company system. Primary energy is supplied to the United distribution system on Manhattan Island and to the Bronx, Westchester, and Queens districts.

Two stations—Hell Gate with a 60-cycle capacity of 500,000 kw. and Sherman Creek with a 60-cycle capacity of 105,000 kw., supply the systems. In addition to the interconnections with the Hudson Avenue Station of the Brooklyn Edison Company, there are connections to the 25-cycle system through five frequency changers aggregating 185,000 kw.

The 60-cycle distribution load on Manhattan is supplied almost entirely by multiple feed low-voltage networks, having a total connected transformer capacity of 100,000 kv-a. Similar networks are in operation in the Bronx and in parts of Queens. Service to the remaining districts as well as the major supply to these networks is furnished through conventional distribution substations. In network districts, however, the building of new substations has been discontinued and the distribution transformers are supplied at generator voltage.

The high degree of service reliability required by high-load density districts, called for a system superior to the usual radial arrangement. This led to development of the multiple feed a-c. low-voltage network which was first placed in service in Manhattan in 1922. Experience with this system of distribution with rapidly expanding application indicates that the reliability of service is now limited by that of the generating sources.

Operating experience has shown that a bus fault on the conventional ring bus arrangement of generator connections with high capacity interstation ties will cause outage to parts of the system and serious disturbance to the remainder.

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The companion papers describe a new arrangement of system connections to the generating sources—synchronized at the load—which applies the principle of multiple feeds upon which the network distribution system is based.

With this arrangement a generator about to be placed in service is first synchronized with an adjacent unit and connected to the bus in the usual manner. After the generator is supplying the load of the bus section to which it is connected, the high-tension connections to the adjacent unit are opened leaving the generator connected only through the low-voltage networks.

In order to check the predictions and calculations and to furnish a basis for operating all generating units synchronized at the load a number of system tests was made.

EXPERIMENTAL DETERMINATION OF NETWORK IMPEDANCE

The proposed arrangement contemplated a system in which the only connections between generators would be those through the secondary network. While the system constants from the generator to the network were susceptible to accurate calculation, there was no information available as to the impedance of the secondary mains system; hence, it was desirable to obtain test confirmation of the calculated values. This test was made on the Times Square Network covering 0.37 sq. mi. with a connected transformer capacity of 11,325 kv-a. supplied by eight distribution circuits. Two of these circuits emanating from a remote substation were out of service during the tests to simplify the determination.

Readings were obtained during light load periods in order to eliminate as far as possible the effect of customer's load. By manipulating the feeder regulator on one circuit while the regulators of the other circuits were kept in a fixed position, values of current, voltage, and power of each circuit and various differential voltages for different regulator positions were obtained, which gave the average impedance.

After subtracting the impedance of the regulators, primary cable, and transformers, the impedance of the network from the transformer terminal points of any

feeder to an imaginary star point, was found to be 5.1 per cent based on the transformer kv-a. connected to the feeder.

The value of 5.1 per cent agrees reasonably well with a calculated value of 4.6 per cent for a similar case when it is considered that the calculations were made on a different network (Inwood) and the network under test was distorted by having two of its normal feeders out of service.

While this value will vary depending on the design of the network, it is felt that 5.1 per cent represents a high value which may be reduced as the load density, on the network, is increased.

SYSTEM TESTS

Calculations made on an arrangement in which one of the generators was connected to the remainder of the system only through low-voltage networks, forecasted successful operation during normal loading and feeder short circuits on the system connected to this generator. Therefore, arrangements were made to test the performance of one generator at Sherman Creek Station synchronized with the remainder of the system through the Manhattan secondary network.

Due to the limited capacity of network feeders available for this purpose, the coupling between the generator thus isolated and the remainder of the system was small when compared to the generator capacity and therefore, the test conditions were more severe than would be expected under an arrangement where the generator capacity and network interlinkings were comparable. The specific purposes of the test were, to determine the stability of a generator operating under such conditions and subjected to feeder short circuits, check the action of automatic network switches having sensitive reverse power settings, and determine the effect of such operation on the customer's service.

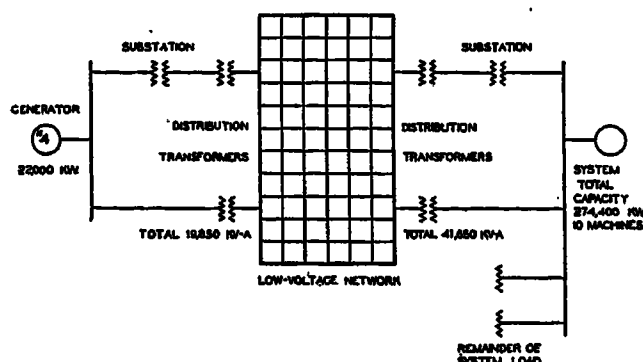


FIG. 1—SCHEMATIC CONNECTIONS FOR SYSTEM TEST

Two 60-cycle systems, herein known as the "auxiliary system" and the "main system," were set up and isolated one from the other except through their connections at the low-voltage networks as shown schematically in Fig. 1. The auxiliary system consisted of a number of 13.2-kv., 7.8-kv., and 3-kv. feeders through which generator No. 4 at Sherman Creek, which has a rating of 12,000 kw. at 8000 volts with 85 per cent power factor and 12.5 per cent inherent reactance, was connected

to the low-voltage networks. The 13.2-kv. feeders of the auxiliary system were connected to generator No. 4 through a bus-tie transformer bank at Sherman Creek. These auxiliary system feeders were connected to the low-voltage networks through distribution transformers, the total installed capacity of which was 19,850 kv-a. The main system consisted of the balance of the New York City 60-cycle system. At the time of the test, there was a total rated generator capacity of 274,400 kw.

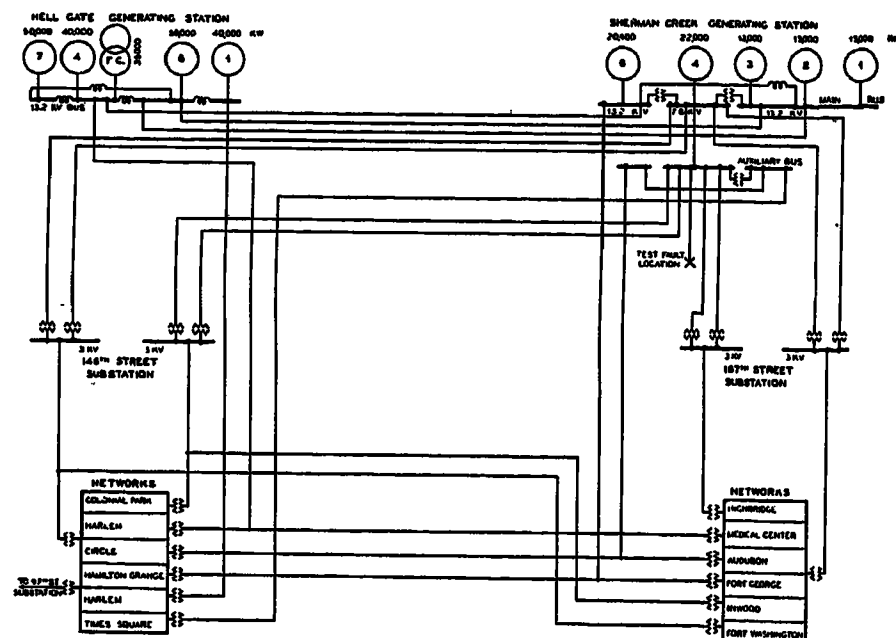


FIG. 2—DETAILED CONNECTIONS FOR SYSTEM TEST

connected to the main system at Sherman Creek and Hell Gate, most of the load of which was supplied to districts other than the networks involved in the test. These generators which are all 13.2-kv. units were connected to the low-voltage networks through various 13.2-kv., 7.8-kv., and 3-kv. feeders, the 7.8-kv. feeders being connected to the generating station 13.2-kv. bus through bus-tie transformer banks. The main system feeders were connected to the low-voltage networks through distribution transformers, totalling 41,650 kv-a.

A more detailed diagram of the system connections directly involved in the test is shown in Fig. 2.

During the test, the approximate loading was 12,000 kw. on generator No. 4 at Sherman Creek and 218,310 kw. on the generators connected to the main system, of which it is estimated 25,200 kw. was supplied to the low-voltage networks included in the test.

A tabulation of the total capacity of distribution transformers involved is given in Table I.

Neglecting the effect of network load, the impedance between generator No. 4 and the remainder of the system including internal reactances of all machines was approximately 60 per cent based on the rating of generator No. 4; 25,900 kv-a. During the tests, all feeder regulators were on automatic operation. All generators on the system are arranged for manual excitation control.

For each test, the main and auxiliary systems were set up, but remained tied high tension through the two selector switches of generator No. 4 at Sherman Creek. Then the load of generator No. 4 was reduced to a

TABLE I
CAPACITY OF DISTRIBUTION TRANSFORMERS CONNECTED
TO LOW-VOLTAGE NETWORKS INVOLVED IN TEST

Secondary network	Type	Installed capacity of distribution transformers in kv-a.		
		Auxiliary system	Main system	Total
Inwood.....	3 ϕ 4 W	3,375.0	5,287.5	8,662.5
Fort George.....	1 ϕ 3 W	1,050.0	1,050.0	2,100.0
Fort Washington.....	1 ϕ 3 W	850.0	675.0	1,525.0
Medical Center.....	3 ϕ 4 W	1,800.0	1,425.0	3,225.0
Audubon.....	1 ϕ 3 W	3,050.0	1,425.0	4,475.0
Colonial Park.....	1 ϕ 3 W	1,250.0	1,800.0	3,050.0
Hamilton Grange.....	1 ϕ 3 W	1,150.0	3,000.0	4,150.0
Highbridge.....	1 ϕ 3 W	1,700.0	1,925.0	3,625.0
Harlem.....	1 ϕ 3 W	1,425.0	4,100.0	5,525.0
Riverside.....	3 ϕ 4 W	1,500.0	5,100.0	6,600.0
Circle.....	3 ϕ 4 W	750.0	6,487.5	7,237.5
Times Square.....	3 ϕ 4 W	1,950.0	9,375.0	11,325.0
Total		19,850.0	41,650.0	61,500.0

value equal to the sum of the loads on the auxiliary system feeders, after which the two systems were separated high tension by opening the main bus selector switch of generator No. 4. After the various tests had been completed, normal conditions were restored by closing the main bus selector switch of generator No. 4.

On May 7, 1928 the two systems were set up and operated synchronized through the low-voltage networks from 8:52 p.m. to 9:57 p.m. Although no short circuits were applied, the machine showed no signs of hunting, and at all times gave stable operation. During the evenings of May 8, 9, and 11, the two systems were set up and a total of nine three-phase short circuits was placed on the auxiliary system, each short circuit being cleared automatically in a predetermined time. These short circuits were made at various locations over a 7.8-kv. feeder, the last three being applied directly outside the feeder reactors at the generating station. The total phase to neutral impedance, exclusive of generator No. 4, for each short circuit is listed in Table II.

Oscillographic equipment was used at Sherman Creek to measure:

- Current and power of short circuited feeder
- Terminal voltage of generator No. 4
- Voltage of main system at Sherman Creek
- Differential between above voltages

(e) Differential watts using current of generator No. 4 and differential volts

(f) Current, power, throttle position, and field current of generator No. 4.

In addition, stroboscopic equipment was used during the tests to view the rotor displacement of generator No. 4 during the disturbances. In order to measure this displacement, a white indicator was marked on the shaft of the generator and was caused to appear stationary by means of a stroboscope which consisted of a neon lamp, a suitable interrupter, a transformer, and a synchronous motor to drive the interrupter. The supply for this synchronous motor was obtained

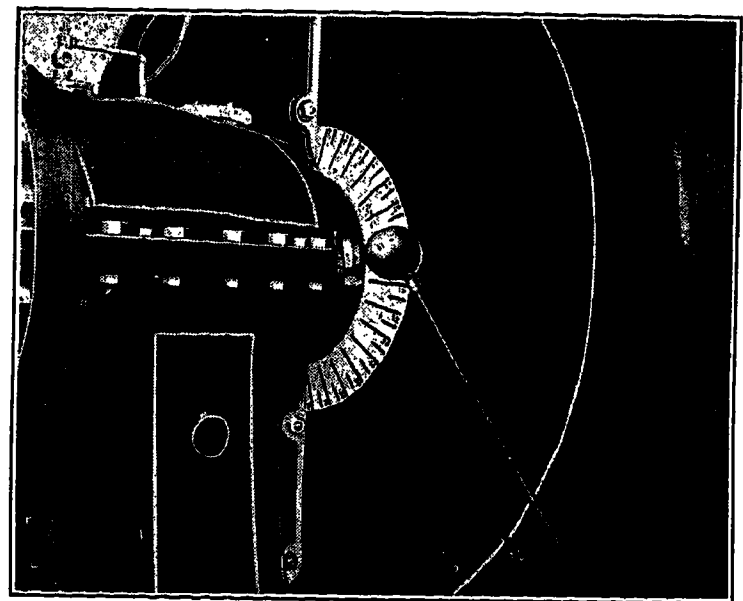


FIG. 3—STROBOSCOPIC IMAGE ON SHAFT OF GENERATOR No. 4

from the main system. The circumference of the housing about the shaft was marked in such a manner that the displacement of the shaft could be read in degrees. See Fig. 3.

Nine recording voltmeters were installed at various locations on the networks to obtain a record of the voltage dip caused by the short circuits.

The total number of network switches involved in these tests was 649, of which 208 were connected to the auxiliary system and 441 were connected to the main system. During all tests, about 53 men were stationed at various locations to observe network switch and relay performance; 492 locations were supervised by operation counters.

TABLE II

Date	Time (PM)	Duration of short circuit (seconds)	Impedance of short circuited feeder in ohms to neutral							
			Sherman Creek reactors		Feeder cable		Substation reactors		Total	
			R	X	R	X	R	X	R	X
5- 8-28	9:00	0.29	0.018	0.888	0.276	0.207	0.015	0.688	0.309	1.783
5- 9-28	8:15	0.28	0.018	0.888	0.276	0.207	0	0	0.294	1.095
5- 9-28	8:35	0.55	0.018	0.888	0.276	0.207	0	0	0.294	1.095
5- 9-28	8:57	0.92	0.018	0.888	0.276	0.207	0	0	0.294	1.095
5- 9-28	9:15	1.35	0.018	0.888	0.276	0.207	0	0	0.294	1.095
5- 9-28	9:41	1.82	0.018	0.888	0.276	0.207	0	0	0.294	1.095
5-11-28	8:20	0.67	0.012	0.654	0.016	0.023	0	0	0.028	0.677
5-11-28	9:02	1.24	0.012	0.654	0.016	0.023	0	0	0.028	0.677
5-11-28	9:20	1.80	0.012	0.654	0.016	0.023	0	0	0.028	0.677

A summary of the results of all the short-circuit tests is given in Tables III and IV. Detailed results of the short circuit applied just outside the station reactors for 1.24 sec. are given in Fig. 4. The record of throttle position showed no movement and is not given. Complete results could not be given for the short circuit of longest duration, made May 11, 1928 at 9:20 p. m., as no record was obtained of the current and power in the short-circuited feeder. This test was no more severe than the one illustrated, as an inspection of Fig. 4 will show that the unit was past its maximum oscillation during that test.

by a feeder short circuit did not exceed the normal kilowatt load on the generator, network switches of the sensitive reverse power type remained closed even under the most severe condition of feeder short circuit. The voltage on the network was sustained at a value which precluded any network switches of the low-voltage release type from operating prematurely due to low voltage. During the test, a maximum of 1.4 per cent of the network switches connected to the machine under short circuit opened and reclosed. These switches opened because the network load at that point was small at the time of test.

TABLE III
SUMMARY SHORT-CIRCUIT TESTS SYNCHRONIZED AT THE LOAD MAY 7-11, 1928

Date	Time	Duration seconds	Load on gen. No. 4 kw.	*Current in short circuited feeder amps.	Power in short circuited feeder kw.	Voltage drop at gen. No. 4 per cent	Voltage drop on networks per cent		†Max. swing of gen. No. 4 during short-circuit electrical degrees
							Max.	Min.	
5- 8-28	9:00 p.m.	0.29	13,500	2010	3800	16	13	8	4 lead
5- 9-28	8:15 p.m.	0.28	11,500	3120	9400	21.5	16	10	8 lead
5- 9-28	8:35 p.m.	0.55	12,500	3090	9400	28.5	21	11.5	8 lead
5- 9-28	8:57 p.m.	0.92	11,700	3120	9400	28.5	21	13.0	9 lead
5- 9-28	9:15 p.m.	1.35	12,750	3120	9400	31.0	21	11.5	15 lead
5- 9-28	9:41 p.m.	1.82	12,750	3120	9400	31.0	21	12	10 lead
5-11-28	8:20 p.m.	0.67	12,500	4720	..	44.5	33	19.5	26 lead
5-11-28	9:02 p.m.	1.24	12,250	4720	800	45.0	34	19	34 lead
5-11-28	9:20 p.m.	1.80	12,900	4720	..	44.5	33	20	40 lead

*Instantaneous symmetrical r. m. s. value.

†As viewed with stroboscope.

TABLE IV
NETWORK SWITCH OPERATION SYNCHRONIZED AT THE LOAD MAY 7-11, 1928

Date	Time	Switches connected to gen. No. 4	Switches connected to system	Switches under manual supervision	Switches with operation counter	Switches opened during short circuit	Switches showing opening torque	*Switches showing operations on operation counter
5- 8-28	9:00 p.m.	208	441	53	402	2	9	4
5- 9-28	8:15 p.m.	"	"	53	"	0	6	..
5- 9-28	8:35 p.m.	"	"	53	"	1	6	..
5- 9-28	8:57 p.m.	"	"	53	"	1	6	..
5- 9-28	9:15 p.m.	"	"	53	"	3	5	..
5- 9-28	9:41 p.m.	"	"	53	"	4	3	12
5-11-28	8:20 p.m.	"	"	50	"	0	14	..
5-11-28	9:02 p.m.	"	"	50	"	2	12	..
5-11-28	9:20 p.m.	"	"	50	"	2	17	4

*Operations varied from 1 to 8 during the test with an average of 1.6 operations per switch on 20 switches.

STABILITY

The test results showed that the generator was very stable when synchronized through the low-voltage networks, though the capacity of the connected distribution transformers was less than would be expected under normal system planning. No hunting occurred and even with the most severe short circuit applied just outside the feeder reactors at the generating station for 1.8 sec., the stroboscope indicated a maximum shift of 40 electrical degrees lead between this machine and the remainder of the system.

NETWORK SWITCH OPERATION

The tests demonstrated that when the system was operated so that the maximum kilowatt load imposed

SYSTEM DISTURBANCES

On the networks which were partially supplied by the machine under test, the voltage drop on short circuit varied from 10 per cent to 34 per cent. It should be noted that this drop was much larger than should occur in normal operation because in the test, the network capacity was distributed in such a manner as to give the equivalent of a two circuit network. In a normal set-up where one machine would carry only a third or less of the network capacity, the voltage drop would be considerably reduced.

SYSTEM LAYOUT FOR INITIAL OPERATION

These tests demonstrated the stability of the arrangement for any disturbance beyond the feeder reactors

and substantiated the general method of analytical treatment.

It was decided to proceed with the layout for operating the entire system synchronized at the load. As there were not sufficient networks to adopt the scheme in its entirety, the 4-kv. substation busses were considered as load points and feeder connections arranged so that the coupling between generating bus sections was provided through transformation and highly re-

check the calculations and therefore it was decided to proceed with operation under this plan and provide automatic recording apparatus which would give test data under the normal system disturbances from which the system behavior under a bus short-circuit condition could be predicted.

Nine element oscillographs were installed at Sherman Creek and Hell Gate, arranged for automatic operation. The principal measurements are those of phase angles between each generating group and a common average system load voltage. The internal voltage of each machine is at all times available by means of pilot generators coupled to the shafts of the main units and excited from a separate battery. The average system load voltage is obtained from a number of feeders through the usual line drop compensators. Various other data are recorded to assist in predictions of system behavior.

In planning the system layout for operating synchronized at the load, it became apparent that the ratio of feeder capacity to generator capacity should be approximately the same for all sections; and that any substation or network district should be supplied from different generating station sections so as to maintain diversified feeds under all operating conditions. The first feature is desirable, not only for load division, but in order that each generating section may carry its share of the system wattless kv-a. The second feature is obviously necessary for service reliability. Furthermore, the feeder grouping and capacity must be such that generating units and also stations may be loaded to their economical point.

The general plan of operating the entire system synchronized at the load, contemplated keeping the tie feeders between Hell Gate and Sherman Creek open at all times. Each of the 13.2-kv. bus sections, four at Hell Gate and two at Sherman Creek, would operate as separate sources during the peak period. The 7.8-kv. bus at Sherman Creek would be split in half and the two sections thus formed tied to the 13.2-kv. busses. During the light load period, Hell Gate would operate in two sections and Sherman Creek as a single bus station. It should be realized, however, that these operating arrangements are flexible and Hell Gate has been operated with various grouping of sections. Fig. 5 and Table V show the system arrangement with unit No. 8 (160,000 kw.) in operation. When generator

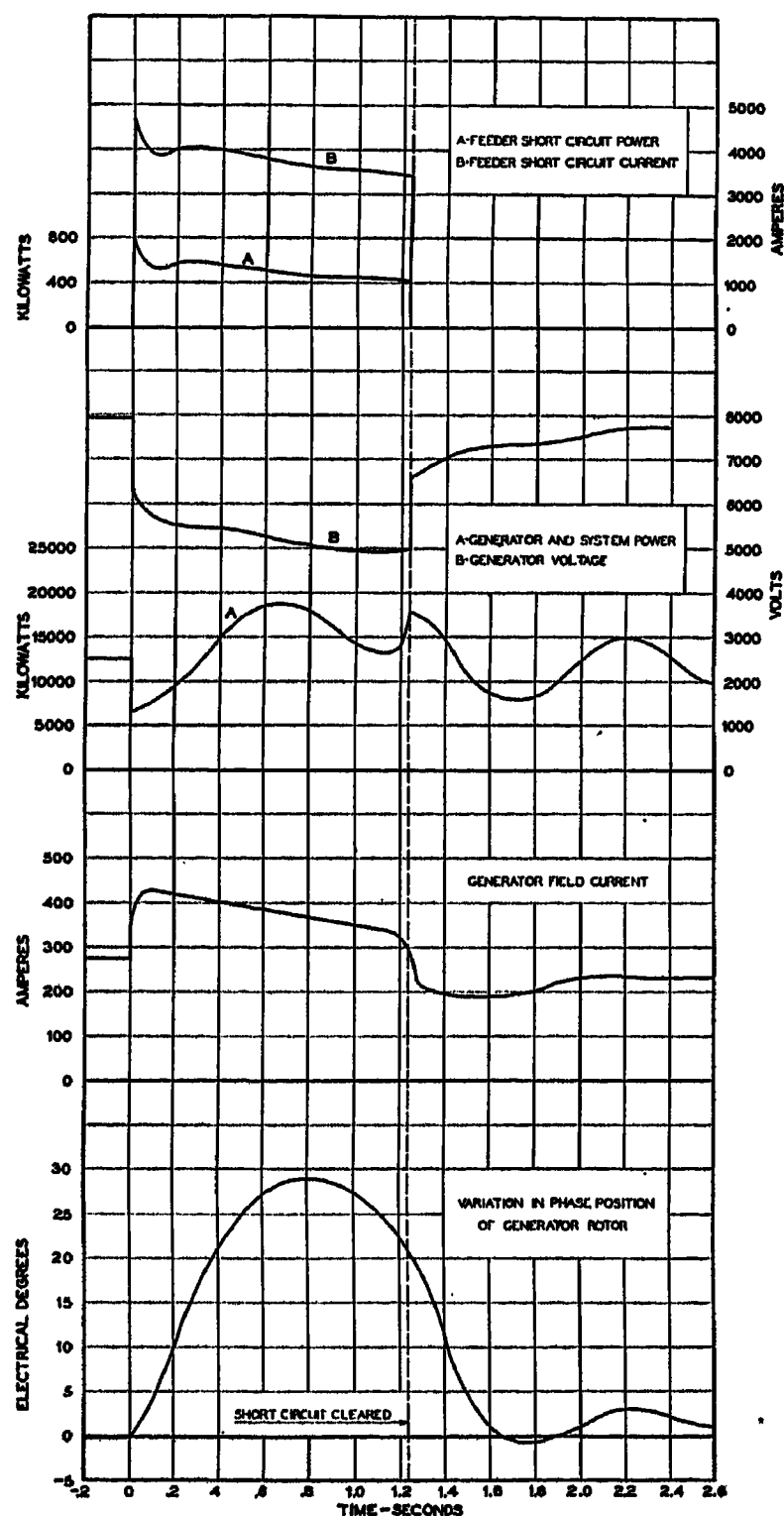


FIG. 4—PERFORMANCE CURVES OF GENERATOR NO. 4 AND SHORT-CIRCUITED FEEDER. TEST OF MAY 11, 1928, 9:02 P. M.

active ties. This was a departure from the original concept, but not from the basic principle, and represents an expedient to be utilized only until sufficient network capacity is available to complete the entire plan.

Calculations made on the proposed connections indicated that under the conditions of a bus short circuit on one section, all generators, except the one short circuited, would remain in synchronism.

It was not desirable, however, to subject the system to a short circuit under this arrangement in order to

TABLE V
SYSTEM CONSTANTS

Bus section	Generator capacity kw.	Ratio generator to feeder capacity	*Reactance tie to system per cent
Sherman Creek NE.....	61,000	0.525	30
Sherman Creek SW....	40,800	0.443	29
Hell Gate No. 4.....	90,000	1.250	50
Hell Gate No. 5-6.....	160,000	0.904	50
Hell Gate No. 7.....	40,000	0.556	50
Hell Gate No. 8-9.....	50,000	0.617	52

*Includes internal reactance of all machines.

virtue of a bus short circuit has disconnected itself from the system, is present. Accordingly, neon lamps, arranged for "bright light" synchronizing have been installed in each substation between the potentials of the various incoming feeders and that of the 4-kv. bus.

In order that a unit may be stable under the condition of feeder short circuit the ratio of short-circuit current to generator full load should not exceed a value tentatively set at 2.5. Table VI shows that the short-circuit

TABLE VI

RATIO SHORT-CIRCUIT CURRENT IN FEEDER TO FULL-LOAD CURRENT OF GENERATOR ON SECTION

A—Peak-Load Condition—Six separate generating sections

Generating section	Machines in operation	Short circuit current ratio	
		Normal case	Special case
SW Sherman Creek....	Generators No. 5 and No. 6	3.33	5
NE Sherman Creek....	Generators No. 4, No. 1 and No. 2 (or No. 3)	2.73	4.05
No. 4 Hell Gate.....	Generator No. 6	1.4	3.45
No. 5-6 Hell Gate.....	Generator No. 8	1.1	2.57
No. 7 Hell Gate.....	Generator No. 7	1.4	3.45
No. 8-9 Hell Gate.....	Generator No. 9	1.14	2.6

B—Light-Load Condition—Three separate generating sections

Generating section	Machines in operation	Short circuit current ratio	
		Normal case	Special case
Sherman Creek.....	No. 5 (or No. 6) and No. 1 (or No. 2 or No. 3)	3.6	5.1
No. 4 and No. 5-6 Hell Gate.....	No. 8	1.1	2.57
No. 7 and No. 8-9 Hell Gate.....	No. 9	1.14	2.6

current ratios are well within limits for all normal cases at Hell Gate. While the limit is exceeded at Sherman Creek, operating experience will tell whether the empirical ratio will require modification. The special cases are for a short circuit on high capacity feeders between the feeder reactor and the step-up transformation and therefore are not considered serious.

With a short circuit on one bus section stable operation is assured if the short-circuit current is divided proportionately among the remaining units. The division of bus short-circuit current under the present operating connections is shown in Table VII. A comparison of Parts A and B of this table shows that the short-circuit currents drawn from the remainder of the system are smaller when synchronized at the load, and the system disturbance will therefore be materially decreased.

REDUCTION OF OIL CIRCUIT BREAKER DUTY

One of the advantages of the proposed arrangement was evidenced in the reduction of oil circuit breaker duty. Hell Gate Station was originally planned for five 50,000-kw., 60-cycle units and the main oil circuit

TABLE VII

DISTRIBUTION OF CURRENT WITH BUS SHORT CIRCUITS

A—System synchronized at the load

3 ϕ short at bus section	Instantaneous symmetrical short-circuit current in amperes						Total
	SW	NE	No. 4	No. 5-6	No. 7	No. 8-9	
SW.....	17,500	3,100	2,400	4,100	1,650	3,450	32,200
NE.....	3,030	21,300	3,070	4,410	2,100	5,280	39,300
No. 4.....	2,400	3,100	28,900	6,920	3,250	5,010	43,900
No. 5-6.....	3,740	4,000	6,170	41,700	6,650	7,900	70,700
No. 7.....	1,610	2,100	3,220	7,250	23,900	6,430	43,900
No. 8-9.....	2,730	4,000	3,400	5,730	4,250	48,300	71,300

B—System synchronized at generating busses

3 ϕ short at bus section	Instantaneous symmetrical short-circuit current in amperes						Total
	SW	NE	No. 4	No. 5-6	No. 7	No. 8-9	
SW.....	17,500	8,650	4,110	6,290	3,480	6,620	46,700
NE.....	7,960	21,300	4,110	6,880	3,780	7,700	50,900
No. 4.....	5,240	5,830	23,900	20,600	9,350	17,300	82,200
No. 5-6.....	6,850	8,220	17,500	41,700	17,100	31,000	121,600
No. 7.....	5,610	6,580	11,500	24,600	23,900	29,400	102,500
No. 8-9.....	6,050	7,750	12,300	25,800	16,900	48,300	116,000

breakers which were rated at 1,500,000 kv-a. were of ample capacity to clear a bus short circuit.

This initial layout was greatly exceeded, and one of the problems introduced by the installation of two 160,000-kw. turbines to complete the station, was the fact that the breakers would be unable to clear a bus short circuit which gave a calculated instantaneous symmetrical value of 2,900,000 kv-a.

With the synchronized at the load arrangement, the duty on oil circuit breakers was reduced and one of the immediate advantages aside from increased reliability, was the fact that maximum duty on these oil breakers would still be within their rated capacity. A comparison of feeder breaker duty before and after synchronizing at the load is shown in Table VIII.

TABLE VIII

THREE-PHASE SHORT-CIRCUIT CURRENT

Bus Short Circuit—Section 5-6—Hell Gate

Time	Synchronized at the load	Synchronized at generating busses
Instantaneous symmetrical	70,700	122,000
Instantaneous asymmetrical	124,000	217,000
0.05	85,000	141,000
0.10	70,000	118,000
0.15	62,000	102,000
0.25	56,000	90,000
0.50	53,000	76,000
1.00	47,000	65,000
2.00	43,500	56,000

With a short circuit on a generating station bus section the clearing time of the feeders connected to this section will vary due to the division of current in the system mesh and to different relay settings. Fig. 6 shows the clearing time of both the primary and secondary line of defense with a short circuit on section 5-6 at Hell Gate. These curves assume that the values of current in the feeders remain constant throughout

the entire clearing operation and the actual clearing times would therefore be somewhat less.

OPERATING EXPERIENCE

The proposed system layout contemplated generator No. 8 (160,000 kw.) being in service at Hell Gate. Since this generator was not available, it was decided to proceed with the program with modifications, using existing capacity.

The modified arrangement was placed in operation on February 13, 1929, when Hell Gate and Sherman Creek Stations were operated "synchronized at the load" with Hell Gate connected to the Hudson Avenue Station of the Brooklyn Edison Company, through the high-tension tie feeders. Tests were made to determine

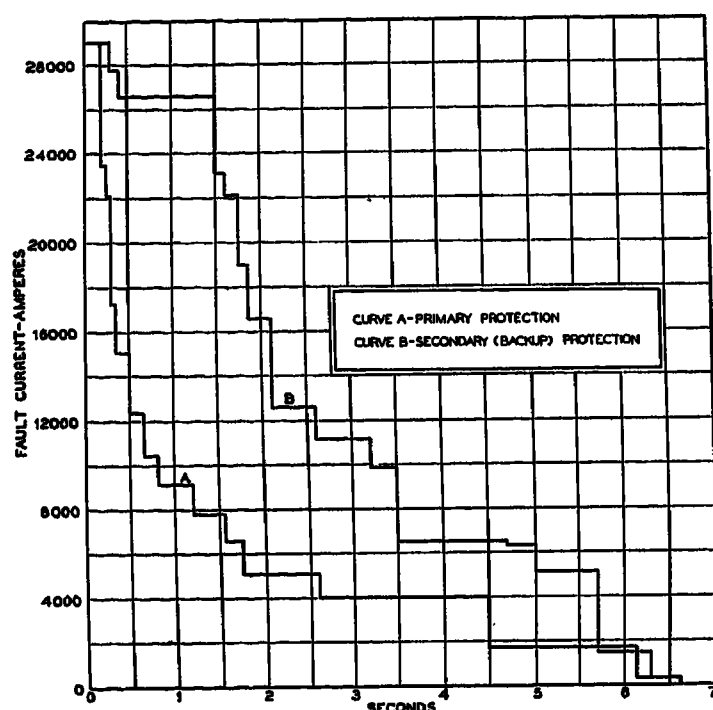


FIG. 6—CLEARING TIME OF FAULT CURRENT IN FEEDERS CONNECTING TO SYSTEM WITH THREE-PHASE SHORT CIRCUIT ON SECTION 5-6 HELL GATE

the extent to which the system wattless kv-a. could be controlled in each of the two generating stations, and in general it was noted that wattless control was more flexible than under the prior arrangement.

The following day, Hell Gate Station was separated into two sections tied together and with Sherman Creek Station, only through the load. The two Hell Gate sections were independently tied to Hudson Avenue.

As the peak load came on, the Hell Gate bus was separated into three sections in the same manner. On March 21, the Hell Gate bus was divided into four sections during peak load: No. 8 generator (160,000 kw.) having been placed in service. Shortly thereafter Sherman Creek Station was also operated in two sections during peak load.

Previous to the new operating arrangement, Sherman Creek, because of its high feeder capacity, was necessarily operated at a lower voltage than Hell Gate to prevent wattless kv-a. overloading. With the set-up of the new system, however, the wattless kv-a. is more easily controlled than formerly. Load may be shifted

TABLE IX
SYSTEM DISTURBANCES WITH FAULTS ON FEEDER 7651

	Per cent voltage variation	
	Synchronized at generating sta. busses	Synchronized at the load
Duration of fault.....	1.67 sec.	2.1 sec.
Hell Gate dip recorder section No. 7 (13.2-kv. bus).....	40	15
Sherman Creek dip recorder (13.2 kv. bus).....	15	3.5
Sherman Creek dip recorder (7.8-kv. bus).....	23	4
147th Street dip recorder (3-kv. circuit).....	24	No record
Elizabeth Street (3-kv. bus).....	No record	6.5
45th Street (3-kv. bus).....	8.5	7.5
97th Street (3-kv. bus).....	8.5	6.5
146th Street (3-kv. bus).....	16	6.5
187th Street (3-kv. bus).....	11	6
Hamilton Street, Queens (2.4-kv. to neutral).....	5	5
Maspeth, Queens (2.4-kv. to neutral).....	26	23
Bronx Edison (2.4-kv. feeders).....	26	10
Bronx Edison (13.2-kv. loop between 188th St. & 172nd St.).....	23	6
Blackwell's Island (13.2-kv. bus)...	46	23
Hudson Avenue (26.4-kv. bus).....	18	6
Brooklyn Edison—66th Street (6.8-kv. bus).....	Over 21	6
Average.....	20.7	9.0

from one section to another by the turbine throttle, up to the point where a feeder becomes overloaded; after which further load shift must be affected by switching banks from one feeder to another, at the substation.

While the main synchronizing path is at present through the 4-kv. substation busses, a number of generating station feeders connect directly to the network. No difficulty has been experienced with the network switches which are of the sensitive reverse power type.

The voltage of the system is considerably less affected by feeder short circuits under the new arrangement. The disturbances caused by faults on a high capacity feeder showed an average voltage drop of 9 per cent synchronized at the load compared with 20.7 per cent with the previous connections.

All generating units have operated in a steady manner both with normal loading and under a number of system disturbances. Records from the automatic oscillographs recently installed will give quantitative information as to system performance.

Test results have verified the calculations, and operating experience thus far has substantiated the predicted advantages of a system synchronized at the load.

Discussion

G. R. Milne: As the new system "synchronized at the load" has been in operation over four months, a summary of the operating experience to date should be of interest.

During the synchronized-at-the-load period there have been 70 feeder faults causing a voltage dip on a generating bus section varying in magnitude up to 33 per cent, but averaging only 2.5 per cent. The voltage at the load is considerably less affected than with the previous arrangement. Comparison of voltage disturbances at two of the Manhattan substations covering a

thirteen-month period preceding and the four-month period subsequent to the start of operations, showed that the dip was reduced 50 per cent.

While most of the paralleling is at present done on the 4-kv. busses, there are in Manhattan alone 321 network switches on generating-station 13.2 kv. feeders connecting directly to networks. No trouble is experienced with these switches which are of the sensitive reverse-power type provided they are equipped with the standard phasing relay.

Of the 70 feeder faults some were of insufficient magnitude to operate the automatic oscillographs; a total of 46 records has been obtained to date. The largest generator oscillation recorded to date was obtained when a fault occurred on a 12,000 kv-a., 13.2-kv. feeder connected to the N. E. section at Sherman Creek. Generator No. 4 swung a maximum of 8 degrees from its normal position.

In addition to the above feeder faults a phase-to-neutral fault which is worthy of attention occurred on Section No. 7 at Hell Gate on June 21 at 6:45 p. m. At the time of the fault—an insulator flashover—Hell Gate was operating in three sections, section No. 4 with a 50,000-kw. unit, sections Nos. 5, 6, and 9 with a 160,000-kw. unit, and section No. 7 with a 40,000-kw. and a 50,000-kw. unit, and a 35,000-kw. frequency changer. The operator connected a section of a reserve bus to section No. 7, the fault developing immediately on the reserve bus. The fault was cleared by the operator after 10½ seconds. Only one of 12 feeders connected to the section opened at the substation end, and two switches on high-tension customer loops opened but with no outage.

The maximum oscillation of the generators on section No. 7 was 2.5 degrees from their normal position, the oscillation of the generator on section No. 4 being 3 degrees from its normal position. Sherman Creek at the time of this fault was operating as a single bus station and the oscillation of the generators was negligible. The line-to-line voltage was reduced 27.5 per cent on section No. 7 at Hell Gate but only 4.2 per cent on the remaining sections. As the fault was line-to-neutral the corresponding voltage was probably reduced 58.5 per cent. The voltage at the load was affected only to the extent of 8.7 per cent.

E. E. Chilberg: Several months ago the company with which I am associated was asked to investigate the stability of the system arrangement described in the present papers. The results of these studies have provided an independent check on the studies made by Mr. Griscom. In general, the conclusions arrived at and methods of study were practically the same as in Mr. Griscom's work. One difference arose from the fact that in the case of the bus fault Mr. Griscom apparently did not investigate the phenomena occurring after the fault is cleared. Our calculations showed that the most severe oscillation would occur after the clearing of a three-phase bus fault and that on this account such a fault would be more dangerous than a feeder fault.

Another difference was that Mr. Griscom did not consider the effect of the synchronous-induction frequency changers. Our calculations were made both including and excluding their effect. Curves A and C of Fig. 1 herewith show the decrement in system voltage for the cases of zero and three frequency changers. Evidently these frequency changers greatly improve the voltage conditions during disturbances. This is due to the special characteristics of these machines which are equivalent to a direct transformer tie between the two systems. Were frequency changers of the synchronous-synchronous type employed their effect on system voltage would be much less. Curve B of Fig. 1 shows the calculated decrement for three frequency changers of this type.

These differences, however, did not change the final conclusion that the system should operate with stability through all normal disturbances.

In addition to studying the characteristics of the particular

system in question, Mr. Griscom has given tentative design constants for any system which is laid out in this way. While this part of the paper undoubtedly represents a valuable effort to facilitate future system layout, we do not believe that it should be accepted too literally, since whether or not any particular degree of synchronizing ability or amount of short-circuit current is acceptable or not depends not only on the expected duration of

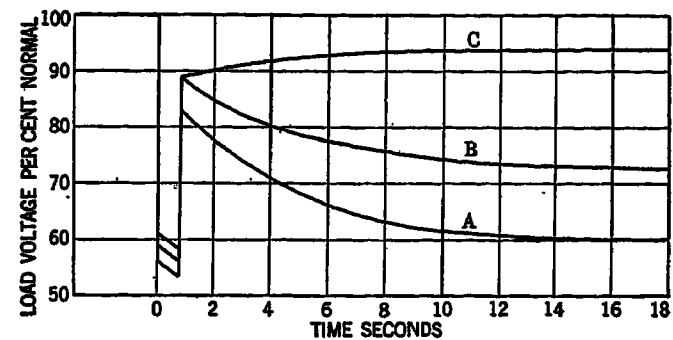


FIG. 1—CALCULATED EFFECT OF FREQUENCY CHANGERS ON SYSTEM LOAD VOLTAGE FOR A THREE-PHASE GENERATOR BUS SHORT CIRCUIT

Curve A Without frequency changers between systems
B With three synchronous frequency changers
C With three induction type frequency changers

faults, but also on the generator short-circuit ratios employed.

In the body of the paper Mr. Griscom states that high short-circuit ratios are not required. While this is probably true in some cases, it should be borne in mind that the use of generators with low short-circuit ratio necessarily tends to reduce the available margin of stability and, therefore, calls for special care in the choice of system layout.

It may be worth while to call attention to the fact that the authors have confined their studies to generators with single windings. The development of generators with double windings has made possible alternative system arrangements. These are illustrated in Fig. 2c and 2d in contrast to the arrangements discussed in the paper which corresponds to Fig. 2a and 2b. It may be seen that apparently the double-winding type of ring bus is a sort of compromise between the pure ring bus of Fig. 2a and the pure synchronizing-at-the-load arrangement of Fig. 2b, while the double-winding synchronizing-at-the-load arrangement might be considered as an extension of the synchronizing-at-the-load principle.

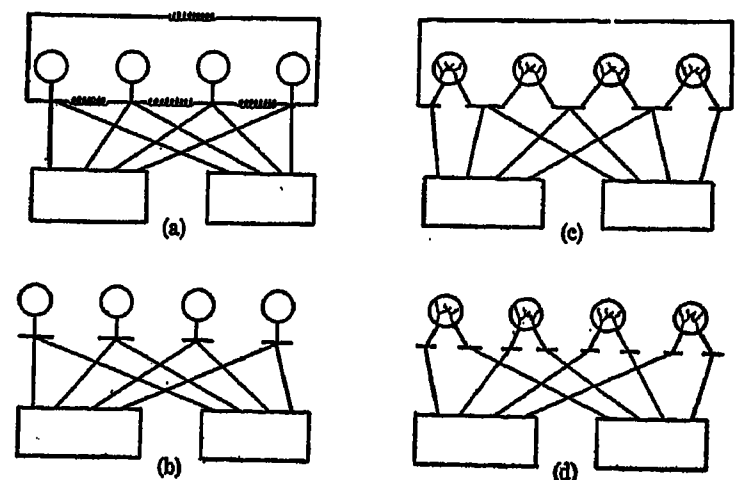


FIG. 2

An important point in connection with the use of double-winding machines is the possibility which they offer of riding through bus faults with stability and without the necessity of dropping off any generators.

This possibility was investigated by calculation. To simplify the calculation equal generators and symmetrical feeder arrangements were assumed. On this account it follows from considerations of symmetry that with a bus fault, generators located symmetrically with respect to the fault will move as a unit. This means that only three angle-time curves need be calculated.

Fig. 3 shows the result of these calculations in the case of the ring-bus arrangement. It will be noted that the angular displacement between generators does not become much greater than 10 or 12 degrees.

Fig. 4 shows the corresponding results for the synchronized-at-the-load arrangement. In this case the maximum displacement angle is around 60 degrees. The greater swing is due to the more unequal distribution of the shock due to the fault.

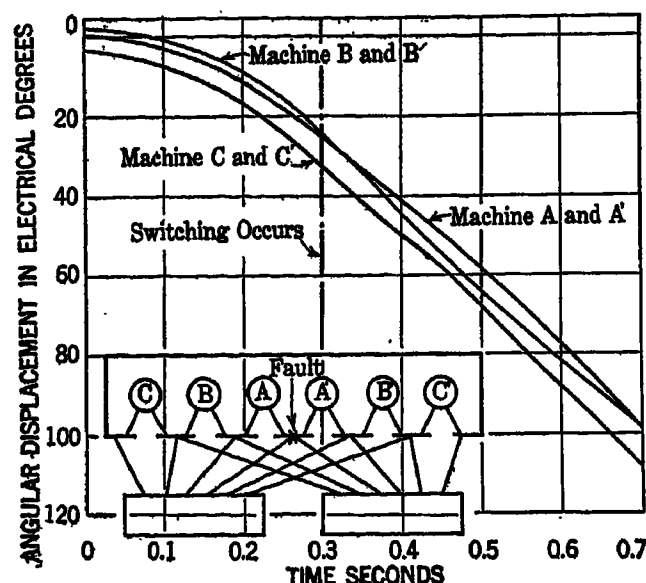


FIG. 3—CALCULATED SWING CURVES FOR A THREE-PHASE GENERATOR BUS SHORT CIRCUIT

Condition previous to fault
Full load on A, A', B, and B'
Two-thirds load on C and C'

From these results it may be seen that with either the ring bus or synchronizing-at-the-load arrangement, the use of double windings permits operation through bus faults without the loss of any generating capacity.

Ability to operate through bus faults is not, however, the only advantage which appears to be offered through the use of double windings. This is illustrated by Table I which compares the single- and double-winding types of machine with respect to, (a) breaker duty, (b) transient drop in system voltage, (c) sus-

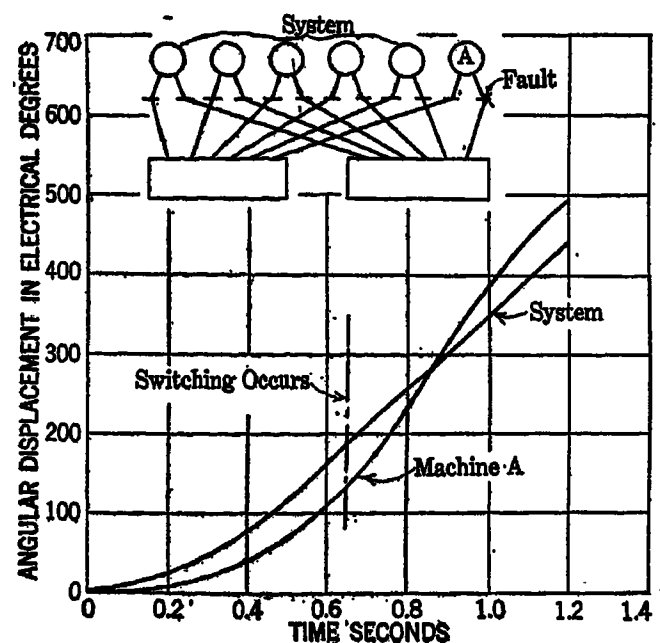


FIG. 4—CALCULATED SWING CURVES FOR A THREE-PHASE GENERATOR BUS SHORT CIRCUIT

tained drop in system voltage, (d) loss of generators, (e) back-up fault protection, (f) load transfer, and (g) sensitivity to feeder faults. By reference to the table it may be seen that in the case of the ring-bus arrangement the only disadvantage in the use of double-winding generators is increased difficulty of load transfer, while definite advantages are shown with respect to breaker duty, transient and sustained drop in system voltage, loss of generators, and back-up fault protection.

TABLE I

	Ring bus		Synchronized at the load	
	Single-winding generator	Double-winding generator	Single-winding generator	Double-winding generator
Breaker duty.....	High	Intermediate	Low	Very low
Sudden drop in system voltage.....	High	Intermediate	Low	Very low
Sustained drop in system voltage.....	High	Low	High	Low
Lose generators?.....	Yes	No	Yes	No
Back-up fault protection.....	Difficult	Intermediate	Easy	Easy
Load transfer.....	Easy	Intermediate	Difficult	Difficult
Sensitive to feeder faults?.....	No	No	Yes	No

In the case of the synchronized-at-the-load arrangement, the difficulty of load transfer and ease of back-up fault protection are equal for the two types of generator, while in all other respects the use of double windings is preferable.

It may, therefore, be concluded that the synchronized-at-the-load type of system arrangement provides an especially attractive field for the application of the double-winding principle.

R. H. Tapscott: The principle of synchronizing generating stations at the load is far-reaching. All systems, however, are not adaptable to this scheme of connections. The 25-cycle system in New York operates with the feeders radial to the converters and synchronized only by ties between stations. The latest unit which will be in operation this fall is a 160,000-kw. double-winding unit. It was selected because it economically obtained high reactance between bus sections without increasing reactance between the load and the system. Benefits were also indicated in limitation of system disturbance and improved stability.

The comparison of the characteristics of these two types of systems just presented is very interesting. The symposium on "Synchronized-at-the-Load" has only been applied to existing systems. The future effect on design with double windings and synchronizing at the load will be interesting, segregation by remote synchronizing carried to the equivalent of the still smaller units by double or multiple windings or the reverse, the larger and more economical capacity units which are coming to all systems subdivided electrically by their windings into units comparable to today's units. This ultimate isolation will increase the reliability and improve economies by reducing the size of the spare unit which will be required in operation.

In selecting the double-winding unit for our 25-cycle system, we have found that we could simplify and also obtain economies in station design by the omission of bus-tie reactors, by oil circuit breakers of smaller rupturing capacity, and by the use of fewer circuit breakers due to the omission of the bus reactors.

The low-tension network system as developed takes advantage of good regulation. If we can do anything with the high-tension feeders to improve regulation, we have improved the network system. With synchronizing at the load and double-winding generators, we can undoubtedly omit feeder reactors even on systems of large capacity and accomplish this result. Possibly this will require the introduction of an impedance device of some type in the neutral, but the usual overvoltage conditions which might result from such devices would not be serious with the system split up into equivalent small units.

I understand a double-winding generator has been built previously but not applied as such. Certainly the independent application of synchronizing at the load and of a double-winding generator is a significant engineering coincidence. I think we have much to expect in the improvement of generating-station and system design in the combination of these two schemes.

E. C. Stone: The plan of system operation explained in this symposium is clearly a definite step in advance. The advantages

that will appeal most strongly to operating engineers are the comparatively high degree of isolation of generating sources and the minimizing of voltage disturbances to service that will result from insulation failures.

The desired results are obtained essentially through a system of connections by which synchronizing circuits between generators are given a relatively high impedance without an increase in the impedance of the circuits over which energy flows from generator to load. A similar principle has been applied to many systems in the treatment of fault currents resulting from grounds. In this case a resistance in the neutral of the power system produces high impedance in the ground fault circuit, thus greatly reducing the disturbances resulting from grounds, but does not increase the impedance of the circuits carrying load.

The power system in New York to which this method has been applied is inherently favorable to the application of the method. It seems evident that the best results will be obtained when the transmission feeders delivering power from the generating plants have a relatively small capacity in relation to the capacity of the generating units, that is, where there is a relatively large number of feeders from each generating unit. Under such conditions, each generator may be tied into a relatively large number of substations, so that the loss of capacity, if a generator fails, is widely distributed over the system. Also, if the capacity of a feeder is relatively small, the voltage disturbance to the system resulting from a short circuit in such a feeder will be relatively small. Another favorable element is found in the fact that practically all of the load is finally distributed at voltages below 5000 so that the relatively high impedance of the substation and network transformers is introduced between the generators and the points of synchronizing. In the example presented, the load of seven generating units is distributed by 80 feeders, equivalent to an average of $11\frac{1}{2}$ feeders per unit.

In some of the other metropolitan systems conditions are quite different. For example, 75 per cent of the entire system load in the Pittsburgh district is supplied over nine 66-kv. overhead transmission lines fed by four generating units, and more than one-half of the load is delivered to the ultimate consumer at 22,000 or 11,000 volts. If the "synchronized-at-the-load" principle were to be applied to this system there would be only two transmission lines per generating unit, so that the failure of one would cause a relatively heavy disturbance. With this condition and with such a large proportion of the total load supplied at transmission voltages, it would not be possible to introduce the high impedance available in New York in the synchronizing circuits between generator units. These conditions, it seems to us at the present time, will very largely prevent our making use of the advantages of the "synchronized-at-the-load" principle of system connections. Nevertheless, we are continuing our studies to find a way, if possible, by which the advantages of the new scheme may be applied to our case.

At the present time, the Pittsburgh system is set up on the power station synchronizing bus principle. Each of the two major power plants is divided into two major sections, the only connections between each section being the synchronizing bus connecting the two power house sections and the trunk 66-kv. transmission lines between corresponding section of the different power stations. It will be desirable to increase the number of sections set up on this basis as the capacity of the system grows. The present arrangement, however, is now working out satisfactorily and the serious transmission system short circuits that have occurred since the present set-up was established, have given very little trouble from the standpoint of inconvenience to our customers.

M. T. Crawford: (communicated after adjournment) What is the relay practise on feeders terminating at substation busses? Is conventional power directional equipment installed on the low side of transformers at substation bus connections and over-current equipment on an outgoing feeder where it leaves the

generating bus section? Where several parallel feeders are from the Sherman Creek N. W. section to the 187th Street substation is balanced relay protection used and how is reliability safeguarded with little or no interleaving in feeder supply to this substation? Is it the practise when off the peak to cut out feeders supplying substations in the same way as feeders direct to networks?

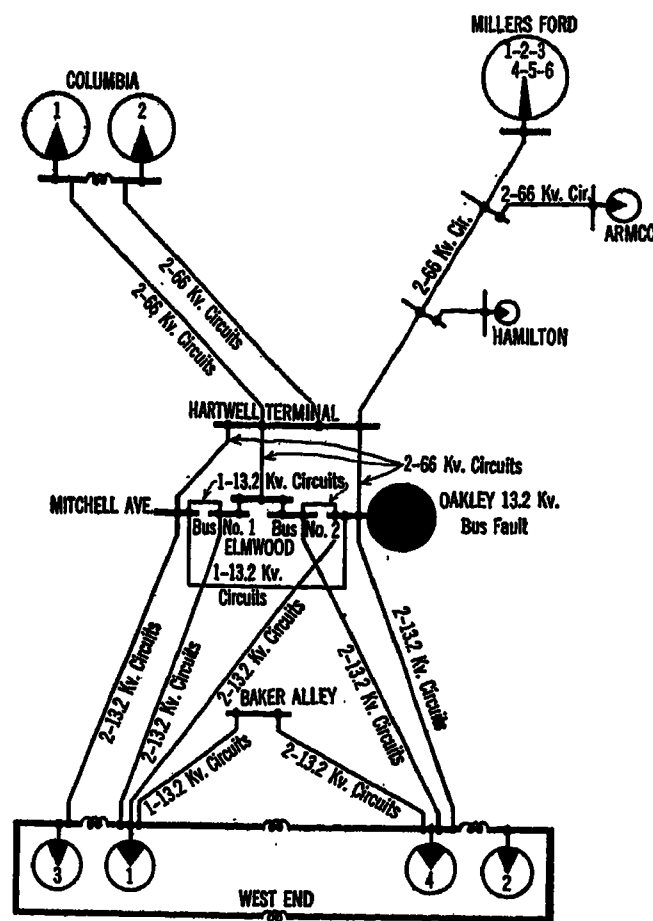


FIG. 5

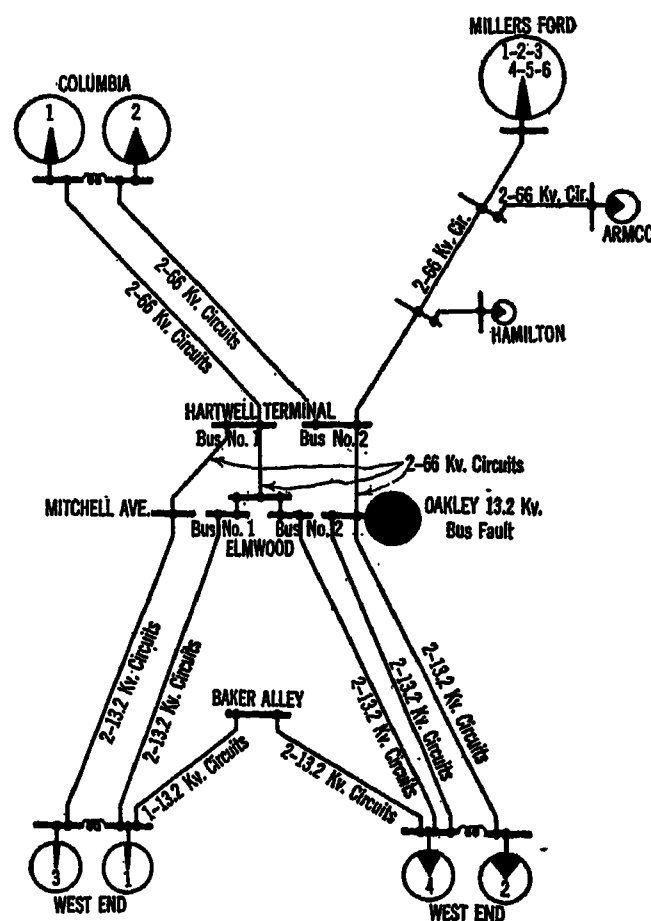


FIG. 6

E. S. Fields: (communicated after adjournment) This discussion of the group of papers on *Synchronized at the Load* pertains to one phase of the subject, that is, segregation of generating capacity. The following remarks refer to the system of the Union Gas & Electric Company, Cincinnati, Ohio.

Fig. 5 herewith shows a skeleton of the system under the present plan of operation, giving the magnitude of short circuit and voltage disturbance on the system associated with a short circuit on a typical 13.2-kv. substation bus (Oakley).

It will be noted that the Hartwell Terminal Substation has all the 66-kv. lines terminating on one bus and that the West End Generating Station 13.2-kv. bus is operated as a closed ring. We have realized for some time two decided operating hazards with the present scheme of connections: (1) a short circuit on the 66-kv. Hartwell bus will affect a great portion of the system load outside of the downtown area of Cincinnati and will remove practically all the load from the Columbia Generating Station, and (2) a short circuit on the 13.2-kv. West End Generating Station bus will affect the downtown area which embodies the Edison System and the low-voltage a-c. network area.

Fig. 6 shows the scheme of connections which it is proposed to use. It will be noted that the proposed connections contemplate operation of the Hartwell Terminal 66-kv. bus in two sections and the West End Generating Station 13.2 kv. bus also

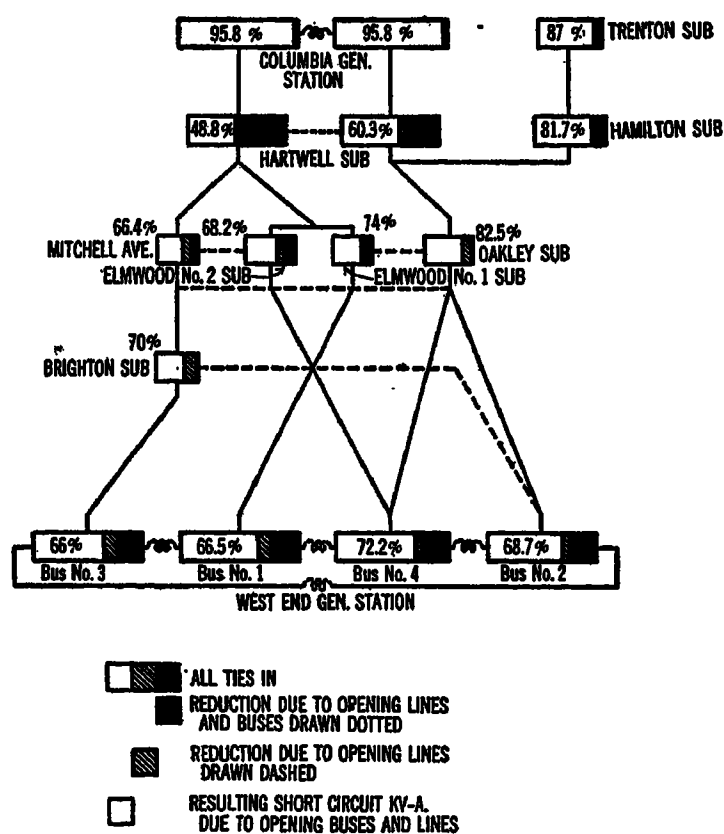


Fig. 7

in two sections. With this arrangement the separate generating stations and the two sections of West End Generating Station will be synchronized through substation busses. These connections will result in a considerable reduction in the operating hazards referred to above with reference to the present connections (Fig. 5).

Fig. 7 shows the reduction that will be obtained in short-circuit current on the various station busses due to the change in operating connections. The change will result in lower oil-circuit-breaker duties, more localized and less severe voltage disturbances, and decided reduction in mechanical stresses imposed on bus construction.

In conclusion I should like to add that we have obtained a large part of the inspiration to carry on our work from a study of the work represented here by this group of papers on *Synchronized at the Load*.

R. D. Evans: (communicated after adjournment) These papers give for the first time, I believe, a discussion of the stability problems of metropolitan power systems. It has been commonly held that on such systems there was no stability problem but only one of reliability of apparatus, lines, cables, and station busses. These papers suggest that there is a stability problem in so far as faults on station busses are concerned. It

is indicated by analytical work and tests that systems synchronized at the load can withstand faults on station busses without the remainder of the machines going out of synchronism. This is a rather new conception and makes desirable the use of the broader meaning of stability.

Synchronizing at the load increases stability, not by increasing the normal synchronizing power between machines, but instead by limiting the severity of system faults and particularly by modifying the system layout so that all machines to be kept in synchronism are accelerated or decelerated as a unit. In comparison with bus-reactor schemes, synchronizing at the load decreases the normal synchronizing power, but increases the stability of the system for station bus faults which constitute the limiting conditions. This results in a better balanced design from the stability standpoint and constitutes one of the attractive features of synchronizing at the load.

In Mr. Griscom's paper attention is called to the fact that certain short-circuit tests were made on a machine having a short-circuit ratio of 0.76. These tests are of particular interest in view of certain published empirical formulas which give the desirable short-circuit ratios for machines on metropolitan systems as between 1.0 and 1.25. During the tests the generator was subjected to a short-circuit current of 2.5 times normal, and the duration of the fault was 1.8 sec. The records of the oscillations show that a longer duration would have been tolerable. This severe condition was withstood without instability, even though no voltage regulators were used. The principal discrepancy between the tests and the empirical formulas is, in my opinion, due to the failure to take into account the voltage support obtained from the other machines connected to the system. These formulas are probably derived principally from consideration of steady-state conditions. Subsequently it has become generally recognized that transient conditions are more severe than static conditions. Furthermore, the tests were made for a system synchronized at the load which is more severe for feeder faults than if the system were connected in the more usual way. These tests lead to the conclusion that machines of a short-circuit ratio less than unity are adequate from the stability standpoint on metropolitan systems.

H. Richter: (communicated after adjournment) Despite the greatest ingenuity on the part of system design engineers, the extensive research and utmost care in the manufacture of apparatus and the most ingenious safeguards by the operating staff, it is still a fact that up to the present time the electrical systems supplying the most heavily loaded areas of large cities have not been entirely proof against serious trouble and sometimes partial or complete shutdown.

The same cannot be said of the latest type distribution system in these areas. It has been proved that with the low-voltage a-c. network system employing automatic network protectors continuity of service can be preserved if proper yet simple precautions are taken. This statement is based on the experience started on Mr. Kehoe's system over seven years ago and now being gradually extended to the majority of the larger cities.

It appears that the method outlined in these three papers opens up one possibility of perfect continuity from the major sources of supply. I believe it is unique in employing a secondary line of defense, the automatic network protectors with their back-up fuses. The reliability in service of these two devices together has been shown to be about 99.9 per cent, which is at least the equivalent of station equipment.

In its resulting improvement of voltage conditions, simplification of system, safer operation, and reduced cost, this new method also parallels the similar advantages of the automatic network in distribution engineering. Another similarity is the facility of starting the operation of a system synchronized at the load without difficulty, just as a secondary network may be commenced without scrapping the apparatus of existing systems of other types.

The low-voltage network has made possible a greater use of diversity between loads on feeders than ever before. Synchronized-at-the-load operation will permit this use to be even further extended, due to the feeders from several generating stations being interleaved and picking up load as they pass through the different sections of the city.

Inasmuch as the most favorable distribution system for use with operating synchronized-at-the-load is the low-voltage automatic network, it is conceivable that where this method of operation is contemplated it will constitute one more reason for developing the network system as quickly as possible.

F. C. Hanker: (communicated after adjournment) Power-system engineering has received increasing consideration during the past several years and engineers have been intensely interested in developments that will maintain the necessary standard of service at lower cost. Metropolitan customers have been educated to expect the greatest reliability of the power supply. The three-wire d-c. system with its supporting battery adjacent to the load gave a continuity difficult to equalize. The a-c. low-voltage network portion of the system, introduced several years ago, has proved its reliability equal to the corresponding d-c. network. For further improvement of the complete a-c. system it became necessary to develop a design that would eliminate the hazard of interruption of the supply to the network.

Design, whether of apparatus or of systems, is always a compromise of what in many cases constitutes conflicting factors. The best performance is obtained when the balance of these

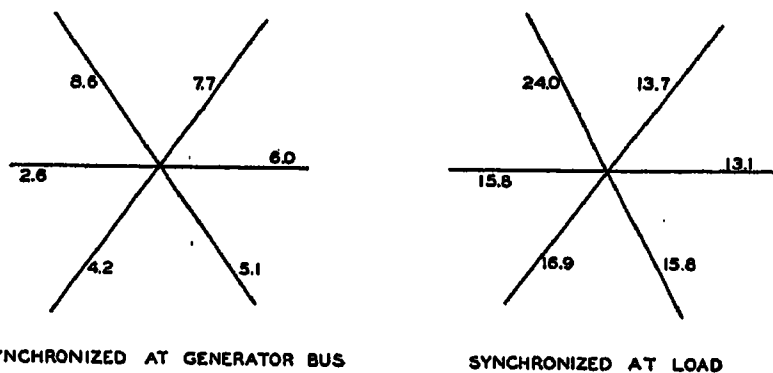


FIG. 8—REACTANCE BETWEEN GENERATING UNITS BASED ON KV-A. RATING OF UNITS OF THE UNITED ELECTRIC LIGHT AND POWER COMPANY

conflicting factors is secured. In the system layout described in the symposium a much better balance has been obtained in the many conflicting factors. The orthodox layout undoubtedly has a larger factor of safety when individual feeder disturbances are considered. It was vulnerable, however, to bus disturbances. In the "synchronized-at-the-load" layout the margin of stability for feeder faults has been materially improved. This is shown very clearly by the accompanying Fig. 8, where the reactances from generator busses to equivalent star point seem to be much increased by opening the station and station ties. In this way a system has been obtained that can successfully ride through disturbances including bus faults without interrupting service to consumers.

There has been a great deal of analytical work done on system characteristics during recent years, but this has been handicapped by the lack of specific records of operation. In the past these records have of necessity been of the statistical type that have unfortunately left many gaps in the complete story of system performance. The operation of a power system during faults is a complicated phenomenon, influenced as it is by all of the electro-mechanical factors that are involved in system layouts. In the symposium the section by Messrs. Searing and Milne gives records of the operation when synchronized at the load that will be invaluable in definitely analyzing the performance of the system when it is expanded to the ultimate. Oscillographic records have been made possible by recent developments in this type of equipment and their importance in studying system operation is becoming rapidly recognized. Therefore, the limitations of

this type of recording apparatus has made it necessary to simulate actual systems by shop and laboratory set-ups. Unfortunately, all factors of the actual system cannot be duplicated with full accuracy and this has necessitated assumptions that have at times cast doubt on the accuracy of the conclusions. It is to be hoped that similar comparative data will be secured on other types of systems so that accurate comparisons of operating performance can be made.

C. M. Gilt: (communicated after adjournment) Since childhood, we have become accustomed to contradictory advice and typical of the differences in the warnings are "Don't put all of your eggs in one basket," and the opposite, "Put all of your eggs in one basket but don't take your eyes off that basket." One thought is based upon the expectation that we may drop one basket but not both, while the other believes that by putting all of our attention on one basket we can avoid dropping it. To some extent, generating stations and distribution systems have apparently been designed according to both recommendations.

While there is no doubt that some of our designs of electrical systems have decreased reliability, as well as increased costs, by too great diversification and complexity, yet I believe most of us will agree that we have not yet been able to design a station that can be operated without some time "dropping the basket" even with undivided attention. It has therefore seemed the part of wisdom, as well as of necessity because of the limitations in oil circuit breakers, so to sectionalize the busses of large, important stations that all the eggs are not dropped at once.

Our real purpose, which would appear to have been lost sight of at times, is not to keep our generating-station busses going but to keep power flowing to every customer with as little likelihood of an outage, and particularly a long one, as is economically possible. The scheme outlined in the papers on *Synchronized at the Load*, recognizes that no bus section and no feeder can be kept free from all outages and carries the diversity of supply from the generator to the low voltage network or substation low voltage busses where substations exist with radial feed from them. The method outlined is most completely applicable to metropolitan areas with generating stations placed in or near a territory of fairly uniformly distributed load; and to a less extent, where generating sources are separated from a concentrated load. The development and operation of the scheme will be watched with a great deal of interest.

In 1922, when the plans for the new 60-cycle system of Brooklyn were formulated, the fundamental importance of diversity from generator to load was recognized, and in 1923 and 1924 when the system began to take form, a similar scheme was installed except that the generating-station busses were tied together through stiff reactors and a synchronizing bus in addition to the 4000-volt substation busses and later the low-voltage network. The substation 4000-volt busses were sectionalized and tied together through 10 per cent reactors and a synchronizing bus which is fed from a spare transformer supplied from a cable ring connecting together various substations. Each feeder bus is supplied by its own transformer and cable from a section of the generating-station busses, no two feeders to any substation coming from the same generating-station section. Ties between generating stations were made at intervening substations, in some cases at the high-tension side of the substation transformers, and in some cases only on the secondary side, so that load was transferred between stations by shifting the substation load from one generating station to the other.

It is expected that when Hudson Avenue Station is complete, no feeders to any substation will be supplied from adjacent generating-station sections. Complete diversification therefore is obtained from generators to substation busses and any generator, generating-station bus, or feeder can be lost without affecting the supply to any customer.

During the early stages of the station, and during the periods of light load, the synchronizing bus has been of real advantage

as a means of transfer of energy from one feeder bus to another, making possible the most economical loading of turbines without tying together of feeder group sections. It also furnished a back-up supply to each generator that was of particular value when the substations were fed by only two or three feeders, and added synchronizing power when the ties through the load were comparatively weak. As the system grows and the relative size of the bus sections decreases, the value of the synchronizing bus decreases somewhat and it must be admitted does increase the interrupting duty on the circuit breakers to some extent. However, it has some advantages, partly associated with its use to transfer power between bus sections making possible the maximum use of feeder copper cross-section and the division of load between generating units and boilers in the most economical manner, and partly as a back-up source of power for each generator. During periods of light load, it permits the reduction in the number of units to a small number without tying together the feeder bus sections and the consequent increase in the extent of any bus disturbance should one take place at such a time.

When the number or size of units exceeds the most extravagant expectations for which the engineers planned, as usually proves to be the case, the synchronizing bus itself may be sectionalized so as to reduce short-circuit duty.

The addition of the next unit at the Hudson Avenue Generating Station will make this necessary and we will either split the synchronizing bus into three or more sections tied together through bus reactors or operate it in two or more distinct sections synchronized through the load whenever the capacity on the bus exceeds about 350,000 kw. or provide the remaining units with double-winding auto-transformers with each winding connected to a separate feeder bus section and through reactors to different sections of the synchronizing bus. The synchronizing bus would then be operated in two sections synchronized through the secondaries of the generator auto-transformers and the load. While data are not yet complete on which a final decision can be made, the last two methods appear to be the most advantageous with the double-winding transformers scheme offering some advantages in stability in case of bus short circuit, though requiring a little more care in the distribution of feeder loads to avoid affecting bus voltages and in this particular case with the size of units under consideration, very slightly increasing the station cost. However, any material increase in the size of units would make the double-winding transformer a relatively less expensive installation.

The papers presented outline a very interesting application of the principle of diversity and separation of supply to the customer. In the type of community and load served, this has apparently been accomplished without increase in investment, and further has permitted a station to grow far beyond the original plans without an expensive change in oil circuit breakers.

S. B. Griscom: It is gratifying to note that the work done by Mr. Chilberg gave results practically the same as those presented in the papers.

Mr. Chilberg is correct in his statement that, in general, the most severe oscillation would occur after the clearing of a three-phase bus fault but this does not necessarily mean that the system is more likely to go out of step after the fault than during the fault. Because of the symmetry, the angular oscillations during a bus fault may be considerably less than the angular oscillations during a feeder fault, but the other system manifestations such as voltage drops would be much more severe.

The curves which Mr. Chilberg shows as illustrating the effect of induction frequency changers are likely to be misleading. They show that, following a short circuit, the load voltage gradually decreases if synchronous frequency changer sets are used, and gradually increases if induction frequency changer sets are used. This result is undoubtedly based on the loss of one generating unit and the assumption that the excitation on the remaining

units is not increased. To a certain extent such an assumption might be justified since voltage regulators are not now in use on the systems in question. However, the inferred conclusion seems to be rather far fetched when it is considered that voltage regulators on the generating units will accomplish the same results; in fact, they will bring the voltage up to 100 per cent instead of 93 per cent for the induction frequency-changer set. The fundamental plan of operation calls for the use of sufficient spare capacity to permit the loss of the largest generating unit, which means that there would be sufficient capacity to take care of the wattless kv-a. demands even if a unit is lost during a bus short circuit. It is expected that no serious difficulty will be encountered without the use of voltage regulators, but if experience should show that the voltage should tend to settle to too low a value following the loss of a unit and could not be recovered quickly enough by the station operators, it would seem that the use of automatic voltage regulators would be a much more economical method of accomplishing the desired results. Where frequency changers are necessary for load transfer, the synchronous-synchronous frequency changer set has a distinct advantage in its ability to generate wattless kv-a., and in the fact that the two systems which it interconnects for power flow are still left independent as far as wattless power flow is concerned, thus minimizing the reflection of voltage disturbances from one system to the other.

The tentative design constants were based upon the general scheme of connection of the system of the United Electric Light and Power Company with standard equipment. Specifically, they assume that feeder reactors will be used and that the generator have normal short-circuit ratio and reactance. Further, relatively long relay settings for feeders from generator busses are used. The design constants were for the purpose of making a ready check of whether contemplated additions would be satisfactory. As such, they require no apology. Experience with actual operation may later indicate that they can be modified, and will probably show them to be conservative.

Referring to Mr. Chilberg's comments on short-circuit ratio, it should be noted that practically all of the generators on the United Electric Light and Power Company's system were purchased before any thought was given to stability or short-circuit ratio. Naturally, any new scheme of operation should be able to use these generators, preferably without placing restrictions on other features of system design. Both calculations and tests indicated that operation of the existing equipment synchronized at the load could be accomplished without compromise or special care in the place of system layout. Such being the case, why should generators of higher short-circuit ratio be used? If the system is safe for both feeder and bus short circuits, of what use is an increase in margin of stability? One might equally well argue that any structure in use today should be strengthened because strengthening will give a greater margin, even if years of experience had already demonstrated its safety. On the other hand, higher short-circuit ratio machines mean higher cost and lower efficiency. Further, if it is really felt that additional margin is required, it can be obtained by using voltage regulators, the first degree being to use a slow-speed system and the next degree a quick-response system. The cost and reduction in efficiency would be negligible compared to raising the short-circuit ratio.

Our studies were not confined to single-winding generators, but since the fundamental plan of synchronizing at the load was the prime question, only those phases dealing directly with the fundamental plan were covered in the paper. The scheme shown as 2 d in Mr. Chilberg's discussion would appear to be the most satisfactory method of connecting the double-winding generators into circuit. While the use of a double-winding generator may prevent the generator from pulling out of step during a brief bus short circuit, nevertheless one source of power supply—the short-circuited bus—is lost. Furthermore, the use of double-winding generators does not necessarily reduce the required amount of

spare capacity since trouble on the steam end may necessitate the removal of the whole double-winding generator.

Mr. Tapscott mentions the possibility of omitting feeder reactors in the future by the adoption of the synchronized-at-the-load and the double-winding generator principles. The possibilities of doing this seem to be very good, even without the use of neutral impedances, provided that the time required to clear short circuits can be reduced. In fact, it appears that if the short circuit can be cleared within 0.4 or 0.5 second, three-phase short circuits can be satisfactorily taken care of using single-winding generators. This would, of course, result in larger voltage disturbances than would be the case if feeder reactors were used.

A. H. Kehoe: It is gratifying to find, in the discussion, general agreement with our conclusions that connecting the New York 60-cycle system so it is only "synchronized at the load" has increased the reliability of generating sources, lowered circuit breaker interrupting duties, reduced service voltage disturbances, and simplified the control of system loads.

Mr. Crawford of Seattle has asked about the relaying of certain of the substation circuits shown in the paper by Mr. Searing and Mr. Milne. This is accomplished as follows:

1. Conventional reverse power directional relays are used at the substation.

2. Balanced relays could be used, but standard over-current relays are used on outgoing generating station feeders.

3. The reliability of 187th Street Substation is not safeguarded for generating-station faults. However, the service supplied by this substation is safeguarded by feeds directly to the networks from other station sections; that is, the interleaving is done at the networks and not at the substation in this instance.

4. On off-peak loads, substation transformer banks are eliminated, but feeders remain alive from the generating station to substation

In conclusion, I wish to emphasize that the "synchronized at the load" arrangement embodies a new principle of system design which may be combined with one or more of other well-recognized fundamental plan elements, such as isolated phases, quick-acting circuit breakers, or double-winding generators. Its use does not exclude the others, although it may in some cases make them unnecessary. Adequate system design requires a careful balancing of all such factors.

It is my hope that among those who have discussed the symposium papers or the many others interested in system design, there will be some who will make trial installations of promising system designs, in order that the electrical industry may profit by the improvements which are likely to be obtained in this field.

Automatic Transformer Substations Of the Edison Electric Illuminating Company of Boston

BY WILLIAM W. EDSON¹

Member, A. I. E. E.

Synopsis.—The Edison Electric Illuminating Company of Boston has adopted a policy of numerous relatively small automatic a-c. substations located at the various individual load centers, this policy being enhanced by the development of a new method of automatic control and by the standardization of the station design.

The rating of a substation is based on the sum of three specially designed transformers each having an inherent 50 per cent overload capacity. Thus, the maximum load is normally carried by the three units operating at their nominal 100 per cent rating, but in emergencies the load can be handled by two banks, the transformer out of service, representing only 33 per cent of the station capacity instead of 50 per cent as in the usual case.

The automatic control consists essentially of load-current relays which switch in or out the follow-up transformers as needed. This operating point for maximum station efficiency equals

$$\sqrt{\frac{2 \times \text{core losses per bank}}{\text{copper losses}}}$$

Serious trouble on any bank will bring in the succeeding transformer. Each transformer has its own

sequence switch so that it may be made leading, follow-up, second following, or manual, irrespective of the set-up for the remaining units. The simplicity of this control equipment is particularly interesting; in fact only the current control and one auxiliary relay are directly chargeable to the automatic control. The circuits and apparatus have several special features promoting safety and reliability.

The construction of these stations has been standardized by the development of standard "blocks" complete in themselves and suitable for being arranged or added, as desired. Thus, for each transformer section there are four types of blocks—high-tension, low-tension, regulator, and switchboard. Such an arrangement offers the advantages of complete segregation of equipment, flexibility in station layout, efficient provision for growth, standardization of engineering and construction, and the satisfactory use of complete bills of material.

This system of control and standardization of construction has been applied to five new automatic transformer substations in the last two years, and the results have been very satisfactory.

* * * * *

THE rapid growth and expansion of the electrical distribution system of the Edison Electric Illuminating Company of Boston has dictated a policy of numerous relatively small automatic a-c. substations located at the various individual load centers. Such an arrangement results in reduced line and feeder losses, better voltage regulation, improved reliability of service, closer balance between the load and the transformer capacity in service, and in a more efficient building program for the substations.

The value of this policy was materially enhanced by the development of a new method of automatic control which was much simpler in both design and operation than the previous schemes. In the last two years, the adoption of this control, along with the standardization of station design, has been applied to five new automatic transformer substations and the advantages are quite apparent.

STATION CAPACITIES

The ratings of these stations are based upon an ultimate of three units, and vary from 5000 to 15,000 kv-a. depending on local requirements, these differences being easily met by selection of the number and sizes of the transformers without detracting from the principles of standardization. Closely associated with this question of unit sizes is the special design of transformers developed some years ago for the Edison Company.

1. Station Engineering Dept., Edison Electric Illuminating Co. of Boston, Boston, Mass.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

First of all, it is essential that a station be able to carry its full load in event of failure of one of the units. Formerly this contingency was met by installing the three transformers of such size that two at full rating could carry the load. This meant that under normal conditions one unit (50 per cent of station rating) and its switching equipment was out of service, which represents an economic loss.

Under the Edison Company's arrangement this situation is met by selecting a smaller size, such that all three would be used in carrying a full load. At a slight additional unit cost these transformers are given a 50 per cent overload capacity by increasing the copper and the cooling surface, so that if necessary any two could carry the full load without exceeding the normal 55 deg. cent. temperature rise. Of course the efficiency of these units would be reduced somewhat during this overload, but as this is an emergency condition the loss in kilowatt-hours is negligible.

DESCRIPTION OF STATION

For a 10,000-kv-a. station, for example, there are three 3500/5250-kv-a., three-phase, delta-star transformers having their maximum efficiency at 75 per cent (probable normal load) of their nominal rating of 3500 kv-a.; that is, at 2600 kv-a. Each bank has a high-tension bus section supplied by two 13,800-volt lines, these sections being connected by bus-tie breakers normally closed. The bank supplies a main and auxiliary bus having six 4000-volt, four-wire ungrounded neutral, regulated, automatic reclosing feeders. The low-tension bus-tie breakers are normally closed, but they trip automatically in case of a feeder fault if all

to bring in the second bank equals $\sqrt{\frac{2 L_i}{L_c}}$ where L_i

is the core or zero load losses of one transformer and L_c is its full load copper losses.² This point averages

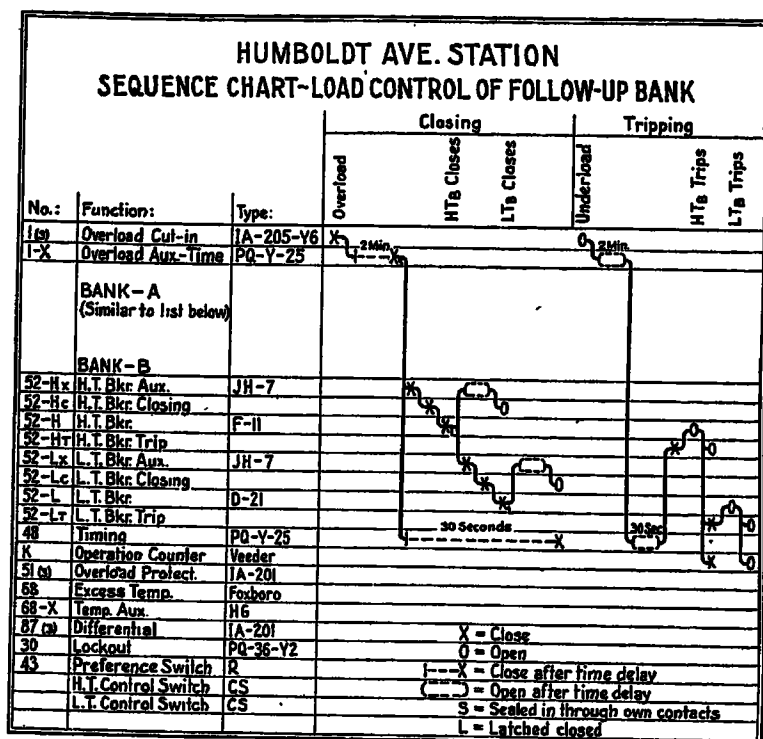


FIG. 3—SEQUENCE CHART—AUTOMATIC STARTING

approximately 105 per cent of the nominal rating (70 per cent of total) for the transformer used, which means the banks are always cool and available for unusual demands.² Since there is little occasion for the transformers to be overloaded (which often occurs with temperature control) the voltage regulation is materially improved.

The relays used for this control (one in each phase) are the G. E. Type IA, the overload contacts being connected in parallel and the underload, or back contacts, being in series. The latter operate at about 90 per cent of the cut-in value. An auxiliary timing relay, Type PQ set for two minutes is used to prevent too frequent operation on a surging load and to reduce the wear on the contacts of the current relays.

In case of overload the cut-in bus is energized, which will bring in any bank or banks whose preference switch is connected to this bus. The auxiliary closing contactor is energized and the high-tension oil circuit breaker closes, which in turn sets up the closing circuit for the low-tension breaker. It will be noticed that when the cut-in bus was energized the protective timing relay No. 48 began to close. By the time it completes its stroke, the high- and low-tension breakers should be closed but if not, or if one drops out due to latch trouble, a tripping circuit is set up and the transformer is locked out.

When the station load decreases the shut-down bus is energized. At the same time the cut-in bus is deenergized which allows No. 48 timing relay to open. When

2. See Appendix.

it completes its operation the tripping circuit for the high-tension breaker is completed and this breaker opens, followed in turn by the low-tension breaker.

A similar set-up would be used to control the third bank through a second set of cut-in and shut-down busses.

b. The question of safety and reliability assumes special importance in a non-attendant station. These are met in the Edison system by providing each transformer with differential protection relays, excess overload relays, maximum oil temperature relays and an over-all checking relay to insure that the circuit breakers do not drop open or pump. Any of these faults operates the lock-out relay No. 30 and trips both breakers.

There are also several inherent features of design which promote safety; such as, only one polarity is taken to the circuit breaker auxiliary switches or to the relay contacts, all relay coils are for continuous duty, no contacts are subjected to unsafe carrying or breaking currents, interlocks are included to make the high-tension breaker close or open before the low-tension breaker, thereby reducing high-tension voltage stresses, the various circuits are arranged so that improper operation of set-up or manual control switches cannot do any harm, and the number of relays is reduced to a minimum.

c. A second operating requirement calls for the

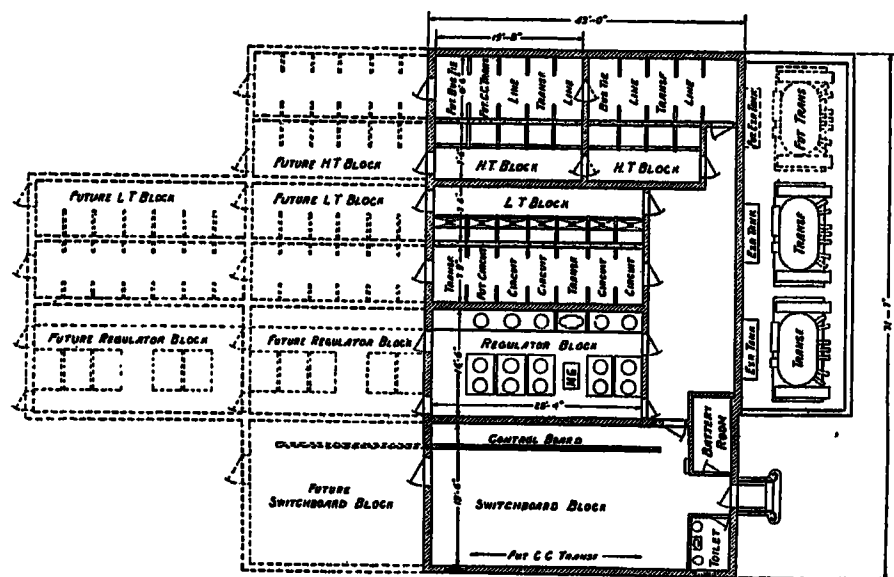


FIG. 4—PLAN OF HUMBOLDT AVENUE STATION

transfer of load to another transformer in case one of the banks is in trouble. This is accomplished by energizing one of the above mentioned cut-in busses by means of the transformer lock-out relay. Here again time is introduced (approximately 30 sec.) before the alternate bank restores the system for the same reasons that timing is used on the automatic reclosing breakers on the low-tension circuits.

Lock-out relay No. 30 removes potential from relay No. 48 which after a time delay drops open. This completes the circuit through the preference switch to energize the cut-in bus which will bring in the next transformer in a similar manner as above.

d. Full selectivity is provided by giving each transformer its own sequence switch so that any bank may be made first, leading; second, follow-up; third, alternate; fourth, out. Manual control switches are connected to this fourth position as a matter of uniformity in operation between stations; otherwise they could be omitted. It will be noted that any of the transformers can be operated independently of the others. For example, one may be under manual control and the rest automatic, or if desired, two may be set up to operate in parallel as a group, thereby permitting two smaller banks to operate as a unit and reducing the number of operating cycles.

1. A high-tension block for the two incoming lines, the 13,800-volt bus and its tie breaker, and the transformer high-tension breaker.

2. A low-tension block for the transformer low-tension breaker, the main and transfer busses with their breakers and disconnects, and the 4000-volt feeders.

3. A regulator block for the feeder induction voltage regulators. The battery motor-generator set and the station power and lighting transformers are located in the space opposite the bus-tie cell.

4. A switchboard block for the control switchboard, battery room, toilet, and the constant current lighting transformers if used.

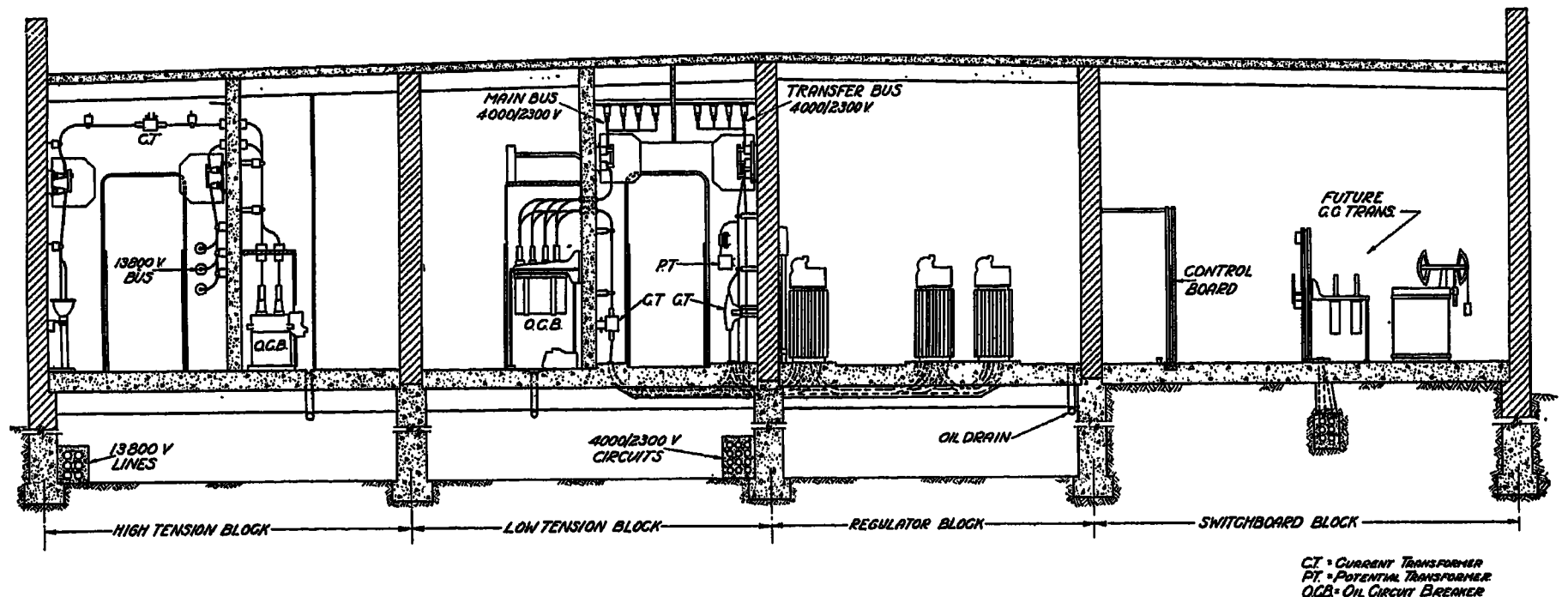


FIG. 5—CROSS-SECTION OF HUMBOLDT AVENUE STATION

MISCELLANEOUS AUTOMATIC FEATURES

The manufacturer's method of automatically reclosing feeder circuit breakers has been revised somewhat to include the safety features and simplicity referred to above.

The battery charging motor-generator normally floats on the control battery, but it will shut down in case of certain faults and will restart when conditions become normal.

A signal is sent over leased telephone wires to the nearest manually controlled station to indicate the opening of any line or feeder circuit breaker, the lock-out of any transformer, or a ground on the 4000-volt system. This latter indication is accomplished by means of a CV voltage relay connected between the system neutral and ground.

STATION DESIGN

The construction of these automatic substations has been standardized as far as practicable. The basic feature which permits this standardization of construction is that the station is divided into "blocks," complete in themselves and suitable for being arranged or added as desired.

For each transformer section there are four such blocks:

ADVANTAGES OF THE BLOCK DESIGN

a. Complete segregation, the blocks themselves forming natural fireproof subdivisions.

b. Flexibility in arrangement to meet land or neighborhood conditions.

c. Efficient provision for the growth of the station by the addition of blocks as needed.

d. Standardization of construction, resulting in the simplification of the preliminary load, land and cost estimates as similar information from previous stations is at hand, the betterment of the price and delivery for the purchase of the equipment due to duplication of former orders, and the decrease in the time and cost of the design installation and operation of the station. Incidentally, it is an advantage to know in advance that the completed station and its operation will be satisfactory to the various departments concerned as the individual standards have already been tried in service and approved.

e. Satisfactory use of an itemized bill of material, this list being grouped in accordance with the station blocks and giving such information as may be needed during the various stages of engineering or construction.

MISCELLANEOUS CONSTRUCTION FEATURES

Each high- and low-tension block is divided by an

eight-inch concrete fireproof wall so that the oil circuit breakers are in one compartment while the busses disconnects and instrument transformers are in the other. Metal lath and plaster cell walls two inches thick separate the equipment per circuit. The regulator room and breaker cells are drained to prevent spreading of any possible burning oil. There is no reinforcement or other steel work carried over between cells. The ground busses are run on insulators to prevent fault currents passing through the structure.

The cell wiring is flame-proof varnished cambric cable. The high- and low-tension cables running to the outdoor transformers have oil-filled potheads to prevent leakage of oil from the transformers which are of the "industrial" oil pothead entrance type. This latter construction eliminates all outdoor structure.

An individual ventilating fan is provided for each compartment so that any room can be quickly cleared of smoke or gases after a fire.

Individual automatic electric heating units with circulating fans are installed in each room for general heating and for preventing condensation.

The general illumination is by alternating current, but floodlights and certain lighting circuits are on a manually operated change-over switch to the battery for emergency use.

Figs. 1, 2, 3, 4, and 5 apply to the Humboldt Avenue automatic substation but the other four stations follow the same general design except for variations in assembly of the "blocks." For example, in the Arlington Substation the switchboard and regulator blocks are located on the second floor.

The construction and operation of these stations have been very satisfactory and it is expected that this type of design will be continued in future stations.

Appendix

Light station loads can best be carried by one transformer as the core losses of two banks would be considerable. As the load increases, however, the copper losses become excessive as they vary with the square of the load; therefore, a point is soon reached where the second transformer should be cut-in. This point to give minimum over-all station losses is that at which the core and load losses of one transformer equals that of two banks, each carrying half the load, thus:

$$L_i + F^2 L_c = 2 \left(L_i + \left(\frac{F}{2} \right)^2 L_c \right)$$

$$\text{or } F = \sqrt{\frac{2 L_i}{L_c}}$$

Where

L_i = zero load or iron loss of one transformer

L_c = copper losses at full load

F = ratio of the load to the rating of one transformer.

The point of maximum efficiency of a transformer is that at which the iron losses equal the copper losses or $L_i = F^2 L_c$

As the average load per transformer may be assumed to be at $\frac{3}{4}$ its rating the transformer is ordered to be most efficient at this point.

$$\text{Then: } L_i = \left(\frac{3}{4} \right)^2 L_c \text{ or } L_i = 0.5625 L_c$$

Substituting in the above formula

$$F = \sqrt{\frac{2 \times 0.5625 L_c}{L_c}} = 1.06$$

Or $1.06 \times 3500 = 3700$ kv-a. approximate point to cut in the second transformer.

The transformers as received vary somewhat from these ratios; therefore, the cut-in point should be calculated from the test results of the actual losses.

Discussion

A. J. A. Peterson: (communicated after adjournment) Mr. Edson's article describes a development which might well be studied for consideration of the resulting improvements in operation and economy. Automatic transformer substations of the kind described have been in service for approximately nine years, and yet the number of such stations in service at the present time is surprisingly small. This may be due either to the lack of appreciation of the possible advantages of such a station, or to the willingness to pay for the core losses of two transformers at all times, rather than suffer the remote possibility of a slight interruption to service.

Mr. Edson stresses the need for simplicity. This can equally well be stressed in any kind of a station, although it seems of more value in an automatic or non-attended station on account of the absence of constant supervision. In analyzing the possibility for simplicity, it is sometimes surprising what features have been considered desirable, and which may very safely be omitted.

The use of a time-delay relay before carrying out the normal switching operation is open to discussion, first, because under usual conditions, the load cycle is comparatively smooth and does not have many small changes, and second, because the load relays which determine the switching point have their own time delay. In addition, the interlocking of the back contacts of the load relays insures further time delay when units are switched out of service. This performance has been confirmed by several years satisfactory operation in several substations.

The time delay for supervising a switching operation seems to be primarily to insure that the breakers close in and stay latched, as trip-out due to electrical fault conditions is taken care of by the use of lockout relays causing the switch-in of the follow-up transformer. Good design and manufacture, followed by good maintenance, are the best precautions against latch failure. It should be possible, therefore, to assume that the breaker will stay closed on the first attempt, unless there is electrical trouble, and the control scheme can be simplified to permit just one attempt at reclosure, thus guarding entirely against any form of pumping.

Unquestionably, the temperature method of control might be desirable from several points of view if it were not for the difficulties of determining the proper switch-in and switch-out points. As a result, the total station load method seems to be the

simplest and most practical method of transformer control, and gives the further advantage of permitting operation in accordance with the actual transformer economy. It does not, of course, permit increasing the rating of a transformer during cold weather, when this might be necessary without regard to economy.

Full selectivity in transformer sequence, that is, the ability to locate any transformer anywhere in the sequence, independent of the others, may be considered unnecessary. However, it seems equally difficult to obtain any form of selectivity and this full selectivity will probably be used until there is developed some simpler form, whereby only the initial transformer is changed in position and the subsequent or follow-up sequence is the same.

Mr. Edson mentions their revision of the manufacturers' method of automatically reclosing feeder circuit breakers. As the manufacturers usually pride themselves on the simplicity of their control equipment, we should be interested in knowing what changes have been made by Mr. Edson in order to obtain this simplification.

The development of the so-called "block" design of these transformer stations is extremely interesting in its effect on engineering and construction cost and time. This development has been carried still further by the utilization of steel cubicles or compartments for the oil circuit breakers, busses, control panels, etc. These units have sometimes been manufactured separately, but have been completely assembled and tested in themselves so as to reduce the time required for assembly in the substation. In other cases, particularly where smaller oil circuit breakers are used, the complete breaker and switching equipment can be assembled with the control panel in a single unit.

The clear and simple manner in which the advantages of this type of station have been presented should lead to further interest on this subject and will undoubtedly result in further development along this line.

Philip Sporn: (communicated after adjournment) Mr. Edson's paper with its stress on standardization is very interesting to me because for years we have been preaching and practising standards in the matter of design and construction on electric power systems. Properly used and applied standards can reduce by substantial amounts the expenditures necessary on an electric power system, but there is always a danger that standards be made a fetish or be made so rigid and so unresponsive to change that after a while the standards merely block new developments. When that point is reached, of course, it is time to throw away the standards since at that point instead of being an aid to progress the standard becomes a definite hindrance. Put more briefly, it is necessary first that the standards be applied intelligently, and secondly it is necessary that they be revised continually.

Referring to Mr. Edson's paper, there are some questions that naturally present themselves upon its reading. First, I note that

the standard transformer is a combination self-cooled, water-cooled transformer. For a number of years now on our distribution systems we have been using a similar combination with the exception of the fact that we have substituted air blast for water. It seems to me that for the distribution transformer which generally carries its peak for a short period of time the air blast is far preferable to water and it ought certainly to be preferable in a location having the low temperatures that are encountered in Boston.

I note that Mr. Edson has installed electric heating in each of his rooms, which is certainly an excellent idea, but I should like to ask why, in a modern substation, advantage is not taken of the development of the storage type of heater. I believe that proper analysis of the capital value of losses by the use of standard heaters will disclose in most instances sufficient justification for the storage-type system. It has of course the further advantage that for an electric utility it means practising what it preaches. If electrical heating is ever going to be anything more than a dream, it will certainly have to be done through some storage arrangement and not through a system that comes on with its demand at a peak period.

The unit room idea is very interesting but it would appear that certain drawbacks to the idea are inherent. For example, it must be very difficult so to treat architecturally a flat and spreading building of the type shown in Figs. 4 and 5 that it will add beauty to the landscape surrounding it; in a residential district this certainly has to be considered today. It is possible too, of course, that such an arrangement would be impossible where land values are high and where such spreading out is impossible.

W. W. Edson: The time-delay features for normal switching and for supervision might safely be omitted as mentioned by Mr. Peterson, but they have been included as these relays are necessary anyway for other purposes.

The overload rating of the transformers questioned by Mr. Sporn is obtained by having sufficient radiator cooling surface and core to allow 150 per cent load to be carried at the standard temperature rise. These modifications are considerably cheaper than the designs calling for water or air-blast cooling. Of course, the efficiency at this overload drops somewhat, but, as explained in the paper, the extra kilowatts lost is not important as this is an emergency condition.

Individual heaters were used for the rooms as they eliminate the need for air ducts or steam pipes running between the various cell compartments and also remove the possibility of condensation or water leaks from steam pipes.

The relatively large area due to this single-story layout is not bothersome as these stations are located where the land values are not high.

I wish to thank Mr. Peterson and Mr. Sporn for their discussions of this paper and am very much interested in the valuable points they have added.

Rehabilitation of Steam Power Plants

BY C. F. HIRSHFELD¹

Associate, A. I. E. E.

Synopsis.—Certain pertinent history of the recent development in the field of power generation is given in graphic form. The problem of rehabilitation of steam power plants is shown to arise from the great rapidity of this development. While no simple rule can be given to indicate when, if at all, rehabilitation is justifiable, certain guiding criteria which may serve as aids in analysis are

stated. These are followed by brief accounts of the various methods available for rehabilitating plants to different extents.

Finally, it is suggested that the possibility of later rehabilitation be taken into account when designing plants for systems in which history or argument indicate that such action is to be expected.

* * * * *

THE exceedingly rapid evolution of the art of generating electric power is known in a general way to all who have more than a casual contact with it. However, even those whose daily business consists of power generation frequently fail to appreciate the speed with which we have advanced or the significance thereof. The graphs shown in Figs. 1, 2, 3, 4, 5, and 6 may serve to visualize the rate of progress. The significance of the development, however, cannot be shown by such curves.

In the first five of these figures the areas within which representative station practise has fallen are indicated by cross hatching and an attempt has been made to indicate what might be called conservative practise or majority opinion by means of a curve drawn through each area. The locations and shapes of these curves must be a matter of personal opinion to a certain extent and no great degree of accuracy can be claimed for them.

The curve given in Fig. 6 is similar to one that has

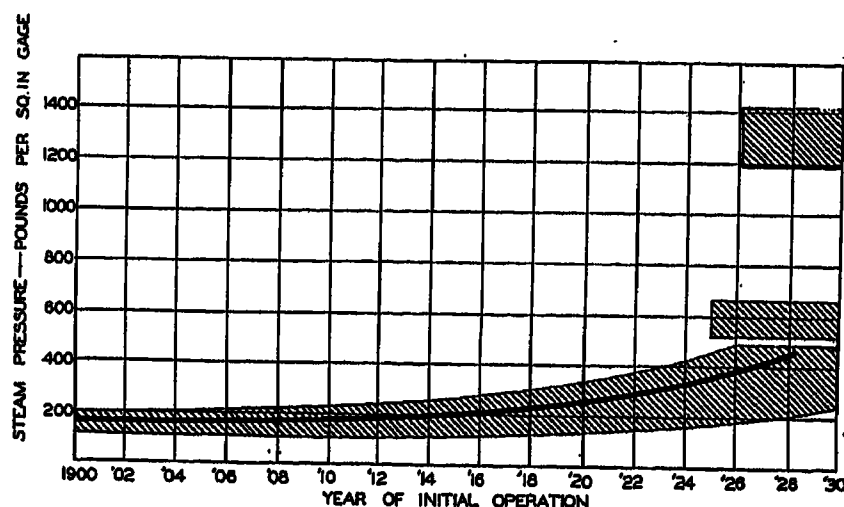


FIG. 1—INCREASE IN STEAM PRESSURES

Shaded areas indicate approximate limits of central station practise

appeared in print several times within the past few years. It represents a remarkable procession in the direction of lower thermal costs. But it appears to be approaching the place where further improvement will be much less rapid. The decreased thermal consumption is, of course, not self justifying because it may have been obtained with more than a

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compensating increase of fixed charges. Unfortunately, experience is not yet sufficiently extensive to make possible a complete analysis. One can only reason from the reports of the few who have actually built and operated the thermally efficient plants. On such a basis they seem to be justified under certain conditions, at least.

The curve of Fig. 7 shows values to which little attention has been given in the literature of this subject. The increasing output per man hour is in line with the general movement throughout the industrial world.

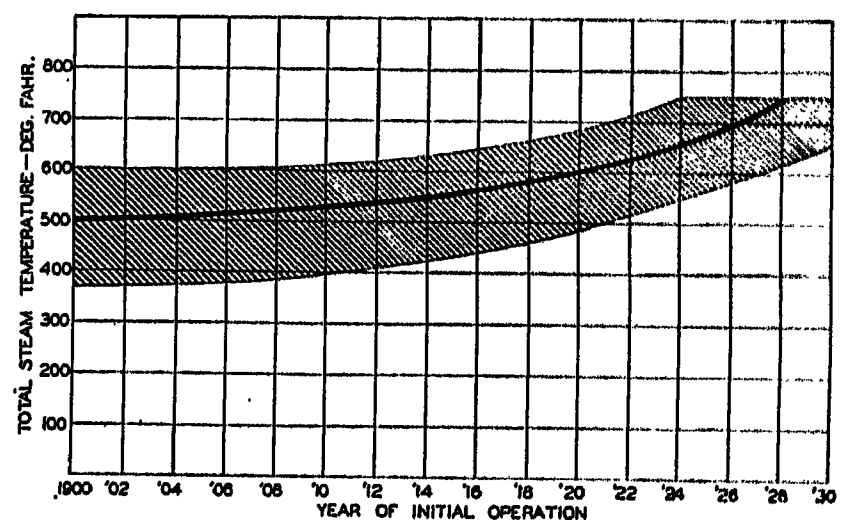


FIG. 2—INCREASE IN TOTAL STEAM TEMPERATURE

Shaded area indicates approximate limits of central station practise

In this case it is brought about largely through improved load factor combined with the use of boilers and turbines of ever increasing capacity per unit. There has also been a conscious effort to design stations in such a way as to facilitate operation and maintenance and thus decrease the number of men required.

From the executive's point of view the rapid advance indicated in these figures has had two opposing results. On the one hand, the total cost of producing power has been decreased. On the other hand, the rate of obsolescence has been high and invested capital has therefore been impaired. The net result of all the forces concerned has been a gradual but consistent lowering of the selling price of power. But the decrease in this price has naturally not been as great as it would have been had it been possible in some magic way to wipe out of existence the older and less efficient plants as more modern ones became available.

The situation from one point of view is shown in Fig. 8. The solid line represents the thermal performance for a typical metropolitan system in which the rate of growth has been rapid. In drawing the line certain liberties have been taken with facts in that the effects of variables other than those here under consideration have been omitted. The dotted line

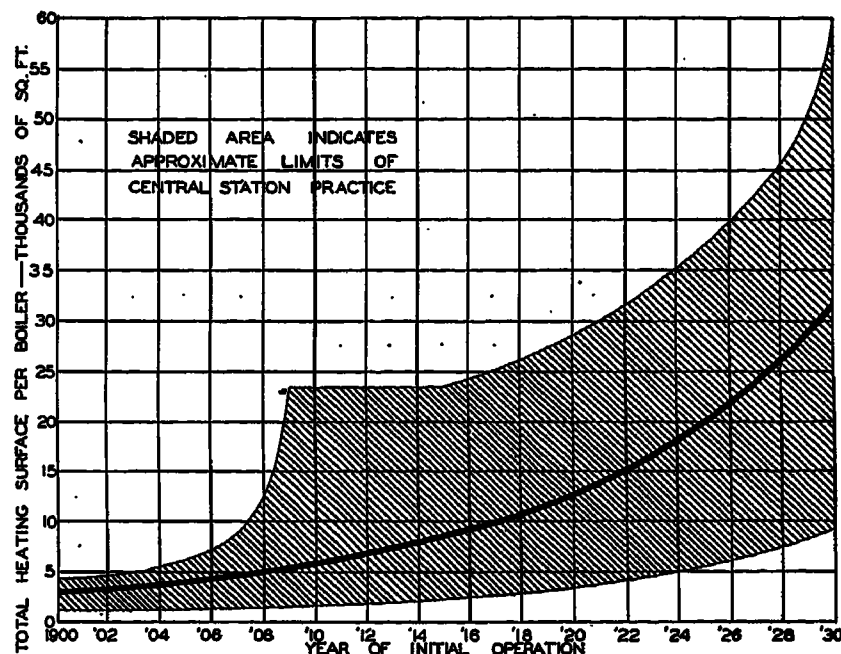


FIG. 3—INCREASE IN PHYSICAL SIZE OF BOILER UNITS

shows what the values would have been if at the time of each improvement all earlier equipment could have been junked and the required capacity obtained with equipment similar to that just installed. One of the problems of the executive of light and power companies is to determine from time to time just how far he is

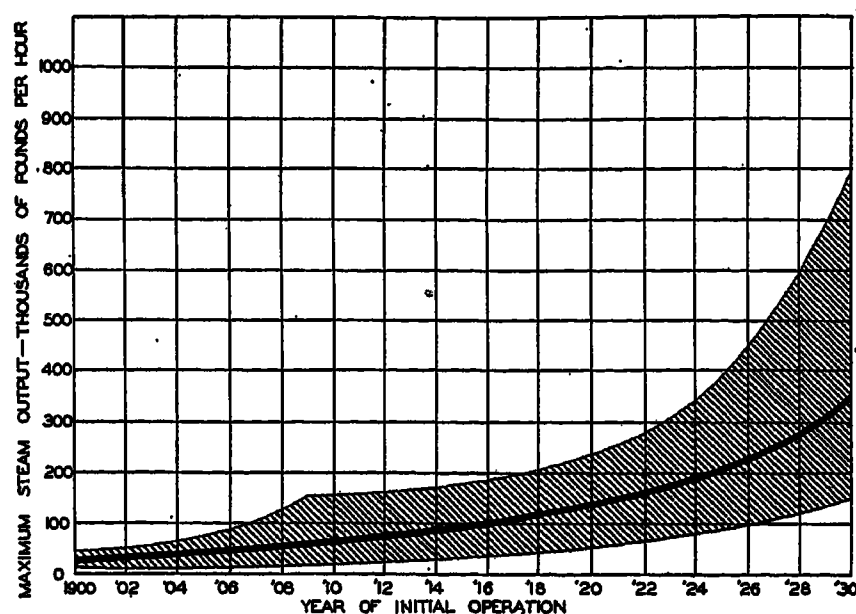


FIG. 4—INCREASE IN STEAMING CAPACITIES OF BOILER UNITS
Shaded area indicates approximate limits of central station practise

justified in moving values such as those shown by the solid lines nearer to those shown by the dotted ones. Putting it in another way, the problem is to determine from time to time that balance between production and capital charges which will represent the best compromise for all concerned. It is out of this problem that we get rehabilitation and reconstruction of power plants.

It is self evident that no simple rule can be set as a criterion of the advisability of such operations. There are too many variables of divergent nature. It is of course true that the old simple rule to the effect that in the limit an improvement must at least so reduce production costs as to balance resultant capital costs

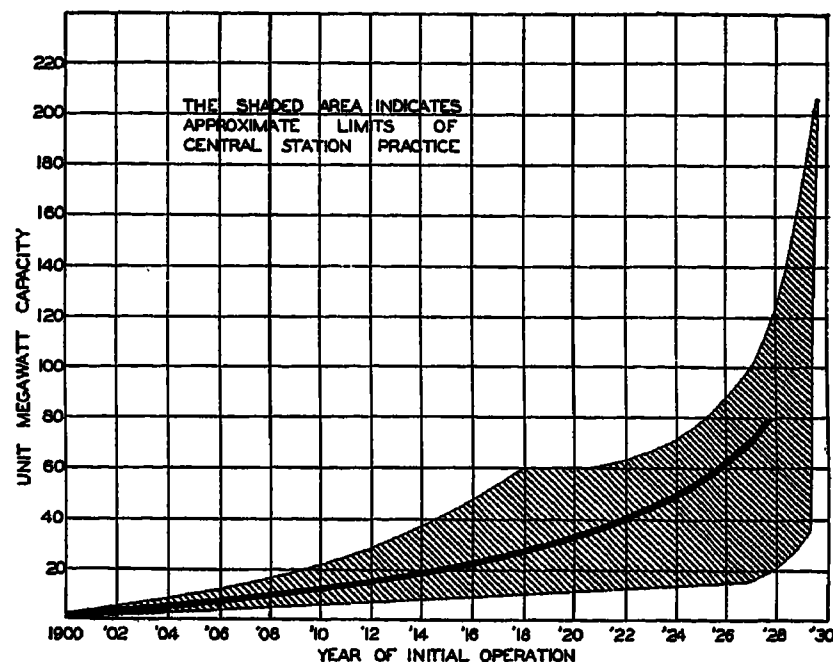


FIG. 5—INCREASE IN MAIN UNIT TURBINE SIZES

holds in a general way. But it is equally true that the effect of improvements upon both sets of costs is, in general, so complicated that exact calculation is very difficult if at all possible in any given case, and a universally applicable formula is practically non-existent. Moreover, there are frequently many almost immeasurable although very tangible factors that enter

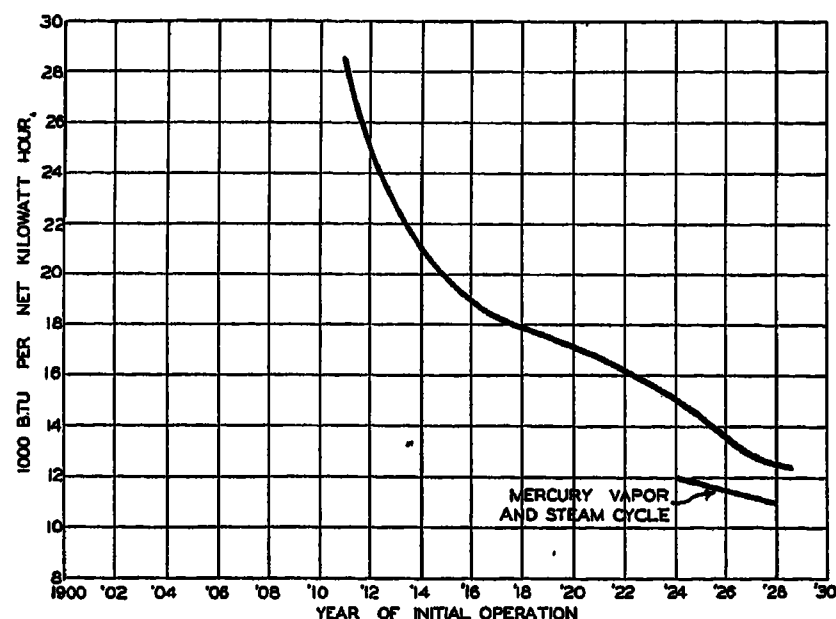


FIG. 6—THERMAL ECONOMY OF PLANTS OPERATING ON 50-60 PER CENT ANNUAL LOAD FACTOR

the problem, so that judgment must to some extent take the place of exact calculation.

There is one very interesting aspect of this problem which should be mentioned at this point. It is the difference between conditions which arise in the case of rapid and slow growth respectively. It happens that most of the light and power companies of this

country have had a very rapid growth. This is a situation very favorable to the maintenance of high standards and low costs whereas with a lesser rate of growth the problems involved are far more complicated. This can be shown very well by using numbers for an assumed case. It should be noted that the numbers chosen are used for simple illustration only and that no claim is made for correctness in an absolute sense.

Let us assume an electric light and power company starting new with a 25,000-kw. power plant which cost

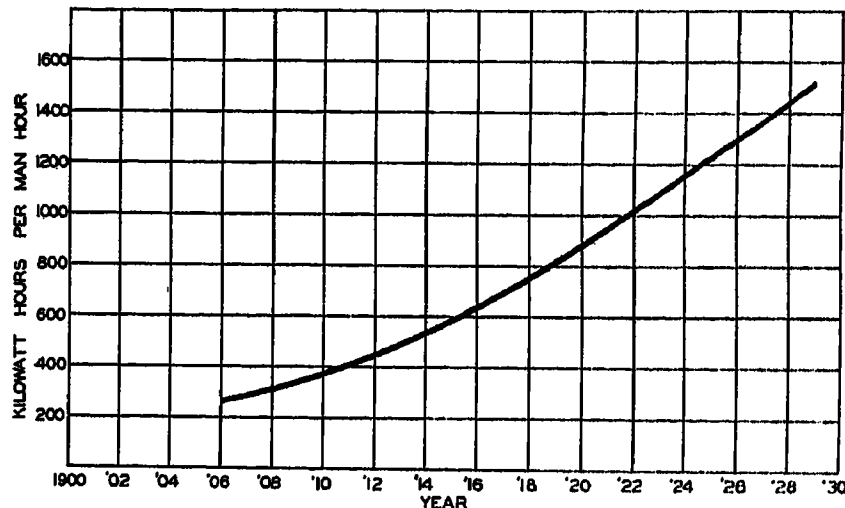


FIG. 7—KILOWATT-HOURS GENERATED PER MAN HOUR

This curve represents operating and maintenance labor for plants characteristic of each year's design practise

\$100.00 per kw. of capacity representing a total investment of \$2,500,000. Let us also assume that the entire cost of the property of the company, including the plant, is two and a half times the cost of the plant; namely, \$6,250,000. If we assume that this company experiences a rate of growth of 10 per cent per year, which is quite conservative for the period of the past 20 years, it will have become a 65,000-kw. company at the end of ten years and a 170,000-kw. property at the end of twenty years. If we assume that investment has increased in direct proportion, the power plant will have cost \$6,500,000 by the end of 10 years and \$17,000,000 by the end of 20 years. The system as a whole will represent over \$16,000,000 at the end of ten years and well over \$42,000,000 at the end of twenty years. It may be remarked here that there are many systems in which the rate of growth has been from one and a half times to twice the rate here assumed.

Inspection of these figures shows immediately that the original investment in power plant becomes in a few years a very small part of the current power plant investment and a much smaller part of the total current investment. When it is realized that extensive power plant rehabilitation can frequently be effected while preserving from 30 to 60 per cent of the original investment, it becomes evident that such rehabilitation in a case of the sort assumed need not affect so great a part of the total capital as to represent any particular difficulties with respect to adjustment of the capital account out of reasonably small reserves. For example, if \$1,000,000 of investment is to be junked it represents

only about 6 per cent of the total investment at the end of 10 years and only a little over 2 per cent at the end of 20 years.

On the other hand, if we assume the opposite extreme, namely, a system which has not grown at all, the old power plant at the end of any given period will represent the same fraction of the total investment as it did at the start. If the scrapping of \$1,000,000 of investment is in question it represents about 13 per cent of the total and presents a very different problem. It is interesting to speculate regarding the size of reserves that will have to be maintained against physical deterioration and obsolescence, if and when the light and power systems of the present day settle down to a rate of growth proportionate only, say, to the growth of population.

Consideration may now be given to some of the things which cause rehabilitation or even complete replacement of power plants. The more important of these are listed below with certain remarks which indicate the conditions under which they may or may not be significant.

1. The plant may be thermally inefficient in comparison with current standards of performance. This consideration is generally significant when the plant in question represents a large part of the total generating capacity and therefore a large part of the investment; when it occupies a strategic position in the system with

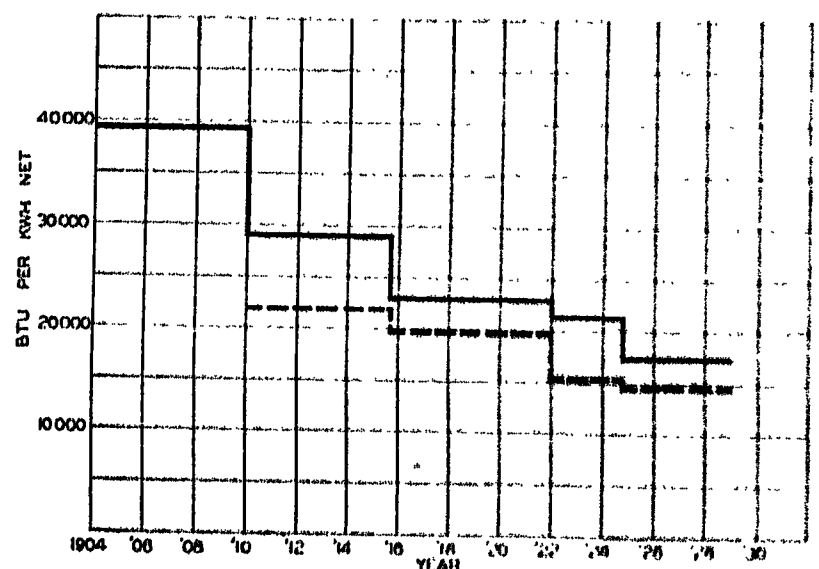


FIG. 8—THE EFFECT OF ADDITIONS TO GENERATING CAPACITY ON THERMAL ECONOMY OF A REPRESENTATIVE GENERATING SYSTEM

The solid line indicates actual conditions while the dotted line shows the thermal economy which would be attained if the older parts of the system were replaced by equipment on a par with the most modern section

respect to receipt of fuel or distribution of load so that its extensive use is required; when it occupies land which has appreciated greatly in value so that the maximum of return must be obtained from it, if it is to be retained; and, in general terms, under any other conditions which make the cost of fuel at this plant a very significant part of the company's annual expenditures.

2. The plant may be inefficient in the use of man power. This consideration is generally not of itself a decisive one but is one that is taken into account in

combination with others. It is serious in cases where labor trouble is to be expected and it may be serious when the plant in question represents a very large part of the total plant capacity.

3. The plant may be inefficient in its use of ground area. This becomes important in the case of land which has appreciated greatly in value, when the plant is particularly favorably located with respect to water or fuel supply and when the load conditions in adjacent territory make greater generating capacity on the site imperative.

4. The plant may be inefficient in its use of invested capital, as by occupying a larger building than necessary, operating boilers at low steaming rates, etc. This consideration is of importance only when the plant represents a moderately large part of the total plant investment or when the location becomes of particular importance for reasons such as those given in preceding paragraphs.

These simple statements should not be understood to indicate that figuratively one can stand off to one side of the problem of rehabilitation and decide offhand with regard to the significance of these controlling factors in any given case. In each case certain rather rough calculations will usually indicate the relative magnitudes of investments, water quantities, and areas and volumes required to obtain certain approximately determined capacities, investments, and thermal performances. Such preliminary calculations will then indicate the impracticability or even the absolute impossibility of certain solutions, leaving a much restricted field for more intense study.

It is practically impossible to set down definite rules or even guides regarding the rehabilitation of steam power plants. A few outstanding facts may, however, be indicated.

In most cases both improvement of thermal efficiency and increased capacity will be possible, and it is necessary at the start of the problem to consider which of these possibilities, if either, is to be favored. In general, increase of capacity beyond certain limits will be attainable only by sacrificing certain thermal possibilities and a clear picture of the relative importance of the two will assist greatly in steering a reasonable course through the maze of things that might be done. Usually the possibility of increased capacity should be given first consideration because certain limits to such increase are so easily discovered.

Thus, it would naturally be foolish to consider increase of capacity if the increased output could not be transmitted or distributed from the site in question. In many cases the available number of routes is limited and these may be found to be used to the limits of their respective capacities. Naturally this is logically the first matter for study.

If the power could be got away if generated, the next logical step is a study of those things which may limit ability to generate on that particular site. These

would be primarily the quantity of water available for condensing purposes and the possibility of delivering the required amount of fuel. If all available water is now being used, as determined either by the supply or the size of canals that must be used, increased output can be obtained only as the steam rate can be reduced, or as the vacuum is permitted to become poorer and the thermal efficiency proportionately sacrificed.

If the water and fuel supply appear adequate the area of the site and area and cubical content of buildings come into consideration. Any of these may place unfortunate limitations on increase of capacity but they are in general not so controlling as the other factors just considered.

Finally, the adequacy of existing switching equipment should be given attention. Any scheme which will permit the use of existing equipment would naturally stand a better chance of financial justification than one which required complete rebuilding of the electrical end of the plant.

With such possible limitations clearly evaluated, the most important decision in the average case and that on which all else may be said to hang, is whether the boilers are to be retained or scrapped. If they are to be retained the operating steam pressure is limited to its earlier value except in those cases where a high-pressure unit is installed as an addition to existing equipment. This will be considered later. If the boilers are to be retained there is definite restriction of choice as to what may be done; on the other hand there is the certainty of a smaller expenditure.

There has been much misunderstanding of the significance of high steam pressure. It happens that a very rapid improvement in the thermal efficiency of power plants has occurred during the same time that we have been stepping up steam pressures. As a result, many who are not familiar with all the details have come to assume that the first is entirely the result of the second. This is really far from a complete statement of the facts.

During the same interval, we have increased the boiler room efficiency from values falling between 70 and 78 per cent up to values falling between 84 and 89. A change from 78 to 88 represents a fuel saving of almost 13 per cent.

We have also adopted the regenerative cycle of operation, that is, heating of the feed-water in steps by means of steam bled from the turbine. This represents a saving varying from 5 per cent to 11 per cent when referred to the coal pile.

It should also be noted that we have, in addition, increased the total steam temperature. In a period of about fifteen years we have gone from a total temperature of about 600 deg. fahr. to a total temperature of about 725 deg. fahr. This change of temperature is equivalent to a thermal improvement of between 4 and 5 per cent for the plant as a whole. During all this time the design of the steam turbine itself has been so improved as to result in a material reduction in heat con-

sumption at any given pressure, temperature, and vacuum.

It is therefore apparent that it is not correct to attribute all of the improvement in the thermal performance of the past ten years or so to increasing steam pressures since many other factors have contributed. As a corollary it follows that in the rehabilitation of a station, it may be possible to do much that will result in improvement of the thermal efficiency even though the original steam pressure must be retained.

The decision with respect to the use of higher steam pressure is not entirely confined to its effect upon the thermal efficiency because increased capacity can be obtained in this way through the use of comparatively small high-pressure turbines discharging into the old turbines, utilizing the old condensers. Therefore, while the boiler room investment would necessarily be high this may be balanced by a comparatively small turbine room investment. The use of the old generators would also, in general, make it possible to use the old switching equipment, although there would naturally have to be additions to take care of the generators of the new high-pressure turbines.

Only one case is known to the author in which complete replacement of old boilers with new high-pressure boilers has been decided on. This is a very special case in which new boilers and turbines are being installed in the old buildings for the primary purpose of obtaining greatly increased capacity from a given site of restricted area. If it is a fact that this is the only case of this sort, it may be due to the comparative newness of high pressures. There are, however, several cases in which high-pressure boilers and corresponding turbines have been added to existing stations with the idea that they would carry the base load and thus take maximum advantage of the higher thermal efficiency produced. Such work is more properly regarded as extension of an existing plant than as rehabilitation of an old one.

The majority of cases of rehabilitation have thus far fallen in the class in which the old boilers are retained, thus accepting the limitations set by the original steam pressure. At present, these are the more interesting and probably the more important.

The following methods of attack are available in such cases:

1. The boiler room efficiency may be greatly improved without materially increasing the steam generating capacity. This can be done by the use of more modern fuel burning equipment of one sort or another, by the addition of economizers or preheaters or both, and occasionally by improved baffling of the boilers.

2. The boiler room efficiency may be greatly improved and, at the same time, the steam generating capacity may be increased to a very great extent. It is not at all impossible to double or more than double the steam output of an old boiler room by using improved combustion equipment of greater fuel burning

capacity, while at the same time bettering the boiler room thermal efficiency through the use of economizers or air preheaters or both. It will generally be found advisable to use a certain amount of furnace wall cooling in such extreme cases so as to gain the increased output most easily and so as to hold in check the tendency toward increased furnace maintenance. In this connection it should be noted that it is frequently possible to obtain greatly increased furnace volume, as by ignoring existing floor levels and by utilizing modern ash handling equipment which requires small height for its installation.

3. The turbine room efficiency may be increased by raising the steam temperature. This will naturally involve more superheater surface or at least differently located surface. In most cases the use of some sort of radiant superheater in series with the older superheaters will be found advantageous but a careful study of pressure drop through superheaters and connections must always be made. This is of particular importance when the steaming capacity of the boilers is also increased. The adoption of higher superheat will usually involve minor rebuilding of the high pressure end of the turbine and in some cases major rebuilding of that end.

4. The turbine room efficiency and capacity may be increased by several different methods. The most obvious, but also usually the most expensive, is by the installation of new, larger, and more efficient turbines taking steam at higher temperature from a boiler room of increased steaming capacity. When this method is adopted it becomes comparatively easy to introduce regenerative feed heating because the new turbine casings will be supplied with bleeder outlets. The improvement of thermal efficiency obtainable from regenerative heating can therefore be obtained readily. Larger condensers or additions to existing condensers may have to be provided. The old electrical switchgear can sometimes be used by adopting a double winding on the generators so that the capacity per switch is held within the old limitations.

A less obvious but very effective method of obtaining increased capacity and efficiency is found in the compounding of old turbines with new turbines. At first glance it would appear as though this would be impossible without raising the steam pressure but this is not the case. Two old turbines may be rebuilt to receive steam at lower pressure and temperature than they did before and to thus serve as low pressure elements to a single new turbine taking steam at boiler pressure. In such cases the extent to which regenerative heating of feed can be obtained will depend upon the design of the casings of the original turbines; naturally the new turbine can be designed for bleeder nozzles and the exhaust connection between it and the older units can be tapped for feed heating. This general method can be made to yield an increased generating capacity of at least 50 per cent and a marked improvement of over-all efficiency as well.

Even when neither of the methods just considered is available it is still frequently possible to obtain increased output by the rebuilding of old turbines and generators. No exact values can be given but increases of the order of 15 to 20 per cent and occasionally even more can be obtained in this way while at the same time materially improving the over-all thermal performance of the station.

5. Even though it prove economically undesirable to replace or to rebuild the old turbines, it is still frequently possible to obtain marked thermal improvement in addition to that which can be obtained in the boiler room. This can be done through modification of the auxiliary power supply and the heat balance of the station. One is inclined to think of regenerative feed heating as necessarily tied to the bleeding of each main unit. In fact, it is obtained to a certain extent whenever that steam which is used for heating feed-water has done useful work before being used for that purpose. From the thermal standpoint it is most perfectly obtained when the steam has done the greatest amount of work before being used for heating and when the heating is done in the greatest number of temperature steps. Practically two or at the most three steps will ordinarily prove economically the best with moderate steam pressures such as one would expect in plants now being rehabilitated.

The fact that comparatively small turbo generators can now be obtained with steam rates that compare very favorably with those of their larger brothers opens up possibilities of effective regenerative feed heating even when the main units are not equipped with bleeder nozzles. Thus, a new unit equipped for bleeding very great quantities of steam may be used to supply auxiliary energy and such part of the station output as may be necessary to produce the required amount of steam. The steam bled and exhausted from this unit may then be used for regenerative heating of the condensate from all main units. Thermally, the result would be the same as that attainable through bleeding of the main units if the steam rate of the small unit were the same as that of the larger. Practically, the result will generally not be quite as good because of the higher steam rate of the small unit.

Certain disadvantages flow from this sort of a tie between auxiliary power and main bus, because of the ease with which electrical trouble can cascade. However, protective devices and schemes of connection now available make the arrangement reasonably safe and thus worthy of consideration in cases of rehabilitation.

It is worthy of note that rehabilitation of the sort which greatly increases station capacity will generally result in a radical reduction of investment per unit of capacity. It is not at all uncommon to obtain the increment capacity at from four- to six-tenths of the investment characteristic of the original station. On the other hand, the rebuilt station is generally more crowded than the original and operating facility may

TABLE I
STATION A
Yearly Output—Millions of Kilowatt Hours

Generating unit year	No. 1	No. 2	No. 3	No. 4
1.....	72.7	92.6		
2.....	155.7	125.6		
3.....	111.8	130.3		
4.....	134.3	122.3		
5.....	118.9	124.7		
6.....	183.4	103.6	2.2	
7.....	169.5	76.5	143.3	122.3
8.....	160.7	119.2	164.8	165.6
9.....	162.3	111.0	197.3	192.1
10.....	153.0	135.3	183.0	198.5
11.....	166.4	129.5	190.2	195.6
12.....	170.5	79.1	154.5	201.5
13.....	160.1	76.4	125.2	162.8
14.....	177.6	63.3	109.7	166.4

TABLE II
STATION B
Yearly Output—Millions of Kilowatt Hours

Generating unit year	No. 1	No. 2	No. 3	No. 4
1.....	8.6	19.0		
2.....	90.2	81.9		
3.....	112.1	115.7	13.6	
4.....	58.2	86.8	92.5	43.4
5.....	95.9	79.4	87.0	103.4
6.....	106.2	102.6	109.1	114.0
7.....	102.6	107.1	110.7	106.1
8.....	123.6	121.7	125.9	123.2
9.....	76.4	75.3	81.6	69.7
10.....	66.2	66.4	69.7	66.4

TABLE III
STATION C
Yearly Output—Millions of Kilowatt Hours

Generating unit year	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
1.....	5.0	3.6	2.2					
2.....	32.2	47.0	35.4					
3.....	48.7	44.6	49.0	11.7	4.6			
4.....	56.5	63.0	64.8	21.1	22.4			
5.....	71.2	70.6	68.6	18.8	26.2			
6.....	75.7	77.7	77.0	22.5	26.4			
7.....	76.3	84.7	59.9	24.9	28.9	54.2	2.2	
8.....	49.1	63.6	62.8	30.6	29.9	116.3	64.4	
9.....	48.1	57.2	46.4	39.5	20.1	89.4	102.7	83.7
10.....	25.1	41.8	35.2	31.9	26.1	84.5	83.9	108.9
11.....	41.0	30.4	28.5	24.8	42.1	115.8	97.3	112.6
12.....	25.0	25.1	32.2	29.3	45.6	111.1	118.9	106.1
13.....	10.1	13.8	15.1	33.9	40.9	103.3	87.3	92.1
14.....	12.2	11.6	14.9	42.6	43.4	101.4	95.6	79.9
15.....	21.9	23.3	25.9	32.6	50.7	109.4	99.3	98.0

TABLE IV
STATION D
Yearly Output—Millions of Kilowatt Hours

Generating unit year	No. 1	No. 2	No. 3	No. 4
1.....	37.1			
2.....	188.0			
3.....	206.8	51.9	9.8	
4.....	188.1	180.2	94.2	33.3
5.....	202.1	86.4	18.2	179.2
6.....	177.5	174.0	176.6	171.5
7.....	173.3	176.8	191.8	162.3
8.....	157.7	184.1	214.5	175.3
9.....	184.8	202.3	183.5	180.8
10.....	160.6	182.0	211.0	179.5
11.....	169.9	144.2	171.3	129.9
12.....	148.2	124.8	211.7	110.9
13.....	183.8	97.7	183.3	106.9

have been sacrificed to a certain extent in producing it. The reduction of man hours per unit of station send out which should follow the increased capacity may therefore be partly counter-balanced through having to use more men than would be used in a new station of similar unit sizes.

It is true that some executive engineers do not accept rehabilitation as economically justifiable in their own systems. Therefore, it is not legitimate in all cases to predicate original station design on the assumption that rehabilitation will be a necessary part of the history of the plant. However, such rebuilding to a greater or lesser extent appears to be becoming more general than it once was and the history of any given system with respect to such practises should be given serious study when designing new plants for that particular system. If it has been one in which rehabilitation has been found economically desirable it is obviously the part of wisdom to design rather generously with respect to ground area, floor area, cubical contents, and clearances, so that if and when rehabilitation becomes necessary there may be the greatest degree of flexibility. It is patent that this consideration should not be used to the disadvantage of the present in order to obtain a questionable advantage in the future. But in the design of any station many decisions must be made on very intangible grounds; the proper values cannot be determined by calculation and the decision must in the end rest upon personal opinion or arbitrary choice. In such cases, it is well to consider the effect of such decisions upon the possibilities of future rehabilitation.

These remarks prompt another line of thought. At the time a station is designed certain economic balances must be struck in arriving at a proper compromise between investment and performance. The factors of useful life and expectable use during that life necessarily enter such calculations. In connection with these there is a fact which is frequently overlooked and which it may be profitable to point out. Few stations are built complete at one time; they are generally built in two, three, or more steps with the process extending over a period of from five to ten years.

While successive steps may be made to embody certain improvements, the general station design and the consideration of operating facility place some real limitations on this process. It follows that such facts ought properly to be taken into account at the time of station design. Thus, if we assume a useful, high output life of, say, ten years as the basis of design and then build serially so that the last unit is placed, say, five years after initial operation of the first, we very materially reduce the period which was assumed as ten years if our other assumptions were correct. The figures given in Table I, II, etc., are taken from real plants and indicate how such things have worked out in some cases. These cases, incidentally, are not at all exceptional.

The comparatively short life at high-load factor of

the later units is quite noticeable in several of the tables. Some also show the comparatively short high-load factor life of the entire station, as for example, Table II, which represents a station which was extensively rehabilitated about twelve years after the first unit was put in service.

Discussion

E. S. Fields: I should like to discuss this paper from the standpoint of the practical application of some of the principles outlined in Dr. Hirshfeld's paper to the electric system of the Columbia Gas and Electric Corporation.

The feature of the program involved was to obtain increased capacity from existing stations, rather than any material improvement in economy. The program required considerable construction work within the West End and Columbia Stations of the Union Gas & Electric Company of Cincinnati, Ohio, and the Millers Ford Station of the Dayton Power & Light Company of Dayton, Ohio. The program resulted in an increased system capacity of 105,000 kw. by making changes and additions to equipment within the existing plants and without making additions to the existing buildings.

The history that led to this program was somewhat as follows: Prior to 1927, studies of the system capacity were centered around obtaining new capacity by extension of existing plants or by construction of a new plant in the territory between Cincinnati and Dayton. During 1927, three of the largest power contracts in the history of the company were negotiated which made it necessary to make an immediate decision in regard to the method of obtaining additional generating capacity. At this time the system capacity of the three main stations in Cincinnati and Dayton was 275,000 kw. An estimate of the load growth indicated that in 1928 the system load would be 250,000 kw. and in 1929, 280,000 kw. The largest unit on the system at that time had a capacity of 45,000 kw.

In order to determine the maximum capacity available on the system with reference to these anticipated loads, a check-up was made of the overload capacity of the machines in existing stations. At the same time an examination was made of the system load duration curve and it was noted that the top 25 per cent of the system load, or something over 50,000 kw., was present on the system only 15 per cent of the time. As a result of this consideration the following plan was evolved:

Construction work on West End Station of the company was started in 1916 and the station put into service in 1918. This station consisted of four 25,000-kw. units. A check was made of the overload capacity of these units and it was found that each machine would carry 32,000 kw. The capacity of the units, however, was limited by the capacity of the generators. Consideration was given to rebuilding the generators for a higher capacity and the cost was determined. The cost of rebuilding the turbine for a higher capacity was also determined. As a result of these studies it was decided to rebuild the steam ends of these machines and install new 36,000-kw. generators. In order to install these generators only minor changes were necessary in the machine foundations. In the turbines, new steel diaphragms were installed between the sixth and eleventh stages, designed for increased steam flow. The boiler equipment at this station was not changed but certain changes were made in the auxiliary equipment.

Extraction heaters were installed in connection with each unit in order to heat additional boiler feed water. Steam driven auxiliaries were changed over to motor-drive in order to work into the new heat cycle. The original condensers having 52,000 sq. ft. of surface were large enough for the rebuilt units. No changes were made in the condensing equipment.

The changes in the electrical equipment of the plant were as

follows: New oil circuit breakers, disconnecting switches, and main leads of higher capacity were required for the larger generators. The main station busbars were reinforced throughout the plant by installing higher-strength insulators and additional copper.

The interrupting capacity of the feeder oil circuit breakers was increased. One of the feeder oil circuit breakers was taken out and tested in the manufacturing company's laboratory to establish its rating. The result of these tests indicated that certain things could be done with the breakers in the way of speeding them up, reducing oil head and so forth, to increase their safe interrupting capacity. It developed from an experience at this same time that the feeder reactor installations in the station were unsafe and reactors on all feeders were changed to a mechanically stronger type with a slightly higher value of reactance to reduce the feeders short-circuit currents to the safe capacity of the breakers.

The total increased capacity obtained at the West End Station was 44,000 kw.

The company that manufactured the two turbo generators installed at the Columbia Station suggested that each of these machines be rebuilt from tandem-compound 45,000-kw. units to cross-compound units of 63,000 kw., by abandoning the high-pressure section of the original turbines and installing separate high-pressure turbines to each of which would be coupled one of the generators that was to be removed from the West End units. The new high-pressure turbine proposed with this change would deliver sufficient steam to the low-pressure end of the original machine to produce 49,000-kw. output on the original generator. Under these conditions the new high-pressure unit would deliver 14,000 kw., making the output of the compound unit 63,000 kw. Two of the generators which were removed from the West End Plant were utilized with these new high-pressure units installed at Columbia.

By changing these units from tandem-compound units to cross-compound units an increased capacity of 36,000 kw. was obtained in Columbia Station.

Space was available for foundations so that the high-pressure unit could be installed alongside the original units.

The steam conditions in this plant were originally 600 lb., 725 deg. fahr. In order to provide additional steam, the capacity of the six standard boilers was increased from 160,000 to 220,000 lb. per hr. In the reheat boilers the steaming capacity was increased from 90,000 to 150,000 lb. per hr. Some of the changes necessary in order to obtain this increased capacity of the boilers were as follows: The air-cooled refractory front walls were replaced with water-cooled front walls. New baffling was installed in the drums. The powdered-coal feeders were equipped with new screws of greater pitch to deliver more coal. The induced draft fans were equipped with new runners and new motors of higher speed to get greater capacity. The air pre-heaters were changed from four-pass to two-pass in order to reduce the friction caused by increased air volume. The boiler pressure was increased from 600 to 650 lb. and the temperature increased from 725 deg. to 740 deg. New impellers were installed in the boiler feed pumps, increasing the pressure from 750 to 800 lb. Evaporators were installed to improve the boiler feed-water conditions. A new 70-in. mill was installed in the central fuel-pulverizing plant to supply the increased demand for pulverizing fuel.

In the electrical end of the station, since both high- and low-pressure generators were connected to the same oil circuit breaker, it was only necessary to increase the capacity of sections of the busses, generator disconnecting switches, and current transformer on the original installation and make the installation of the high-pressure generator and its accessories.

The generator oil circuit breakers were originally rated at 3000 amperes. With the high- and low-pressure units operating in parallel through the same oil circuit breaker, the maximum current was 3250 amperes and the space was limited so that larger

breakers could not be installed. A test was conducted on the breakers to determine the conditions of heating at this higher current. It was found that the only point of high operating temperature was in the top casting of the switch. This was changed from steel to alloy, and the switch operated satisfactorily at this higher capacity.

At the Millers Ford plant of the Dayton Power & Light Company, there was building space available for an additional unit. A new turbine was purchased and one of the generators removed from the West End Station was installed with this turbine to complete the unit. It was necessary to reconnect the generator used in this installation from 13,200 volts to 6600 volts. This addition increased the capacity of this station 25,000 kw. A portion of this capacity is in effect reserve turbo generator capacity at this time since no work has been done in the boiler room to obtain greater steam capacity. This step has been delayed until the system requires the additional firm capacity.

The program as outlined utilized three of the four generators which were removed from West End Station and the fourth generator now remains on the system as a spare.

W. S. Lee: A power generation paper can be very voluminous and have a great number of plants described therein. This was not the purpose of this paper, but the idea was to impress upon both the designing and executive engineer the importance of rehabilitating a plant only when it was a proper thing to do for service and financial reasons. It also brings before the engineering profession in this day of mergers and larger installations and generating units that we must be prepared to do away with many small units that are operating.

The question of selecting pressures prompts me to suggest that you go into this matter a little more slowly than we have been doing recently. I do not mean to say that I decry high pressures, but high pressures do not fit every job. You can build some large plants with lower pressures, and when you apply the operating cost as well as capital cost, you will find that the high pressures do not act as a panacea for all your troubles.

W. J. Foster: I am reminded of the time when hydraulic generators were relatively more important, you might say, than at the present moment. It has always been possible to do more in the rehabilitation of such generators than of steam turbine generators for the reason that most of those machines were made when the standards required close regulation and operators had to take care of the potential and the load changes by manipulating the rheostats by hand. Since such generators were made with a much higher short-circuit ratio, it has been possible in many cases to redesign the armatures so that the same rotor or field with the same excitation will give a much greater output and it is entirely satisfactory to do this since field regulators will take care of the potential, which we did not have in the old days. We can usually make a good showing on an old hydraulic plant in rehabilitating the generator.

In the case of steam turbines, the older turbines were of much lower speed than is now advisable, so that the unit as a whole has to be replaced, and that, of course, causes the generator to be scrapped.

Mr. Fields speaks of the Columbia Gas & Electric System. After an interval of ten or twelve or fifteen years, there have been in the past and probably will be in the future improvements made by which greater output will be obtained with the same material, that is, increased output of 10, 15, or 20 per cent. Nothing like a 50 per cent increase is to be had there, which is possible in many of the older hydraulic plants.

I think it is good policy on the part of the consulting engineers and engineers of operating companies to insist upon conservatively rated generators in the first place. It is so often found possible by increasing the pressure and the temperature or something connected with the steam end to obtain a greater output. If the generator has been conservatively rated in the first place, it is generally possible to operate it entirely satisfactorily and safely at greater output.

L. W. W. Morrow: I want to compliment Professor Hirshfeld on a very masterly paper on a very difficult topic. Anyone who generalizes about power generation and power cost today is dealing with a hazardous subject. Yet it is the one important topic confronting engineers in the utility field today.

Today we are facing a period of increased investment per unit of output, decreased sales price per unit of output, and a longer time for capital turnover. The power station end of the system, roughly, represents one-third of the investment and one-third of the sale price of the energy we are selling.

It is very significant, as Dr. Hirshfeld shows, that in 1908, our best station practise represented 32,000 B. t. u. per kw-hr.; in 1918, it was down to 18,000. Today it is around 12,000. In other words, for a little handful of coal today, costing one-tenth to three-tenths of a cent, you are getting the use of a kilowatt for an hour. So much for the fuel cost.

What about the capital charge to get that result? On an average, we can say that power station of 1908 and 1918 and 1928 cost roughly, \$100 a kilowatt. We can also say that the range today is probably greater than it was in those two periods and under certain conditions is from \$65 to \$140. Thus power-generating engineers have made an enormous increase in thermal economy and without increasing the capital investment materially. Now we wonder where they are going next.

Dr. Hirshfeld very candidly says it doesn't appear that we are proceeding at the same rate as in the past. When we look ahead at this industry with power production doubling every eight or ten years, which means we are adding now 1,500,000 to 2,000,000,000 kw. of new capacity each year, we begin to see the dollar values involved in making engineering judgments on rehabilitation of existing plants or on new power-station building.

In rehabilitating a plant, we have to take into consideration the period ten years ahead just as we do in building a new station. The same factors enter in. One element Mr. Lee touched on is the system reserve requirements which not only involve the power-generating engineer but the transmission and distribution engineer. One element which is very important is to improve the load factors of these systems. To get more kilowatts out of this capacity, we have to find more uses and more hours of use for the power we have available in these stations.

Another factor that is coming into the picture is this: We hear a great deal of discussion about making power as a by-product of coal some combination of the gas, the chemical, and the power industry. This may come about and may make for some cost reductions—nobody can tell. But people will have to use more chemicals and pay more money for them before that is possible.

The third element is that it may be we will find something beside water to deal with in producing power from fuel. We have worked the water cycle to the limit. We have achieved good results with mercury, and it isn't beyond the scope of possibility that we will use some other fluid and gases.

Sidney Withington: (communicated after adjournment) I should like to emphasize Dr. Hirshfeld's thoughts that the increasing operating economies are to some extent counterbalanced by the increasing capital expenditures represented in modern power-plant design. I believe there is some tendency in certain instances to overlook this in a constant effort to add to operating economies.

Dr. Hirshfeld says that the net result of all forces concerned has been a gradual but consistent lowering of the selling price of power. It would add very much to the paper, I believe, if Dr. Hirshfeld would present figures showing the trend of costs of power during the past few years. It would be necessary, of

course, to make corrections for increasing costs of labor per man-hour, and increasing costs of fuel, and possibly a few additional assumptions such as the development of the facilities for burning lower grades of fuel. Such data would, I believe, be of great interest to those concerned with the problem of power production and use. The information might be plotted coordinately with some of the other graphs presented. A segregation of fixed or annual charges and energy, would probably be desirable in order to take into account variations in load factors. After all, it is the final answer which counts and unless that is indicated the whole story is not told.

Philip Sporn: (communicated after adjournment) Dr. Hirshfeld's paper is, I believe, particularly timely in this day of the popularity of the slogan in connection with power systems, such as, "More kilowatts per dollar of investment" and similar slogans. What all of these get down to, is this, that the power producers are spending too much money for facilities to take care of business at the rates they have to offer to get that business. Obviously one way of getting around this situation is not to spend so much money per kilowatt of capacity.

Dr. Hirshfeld has given the entire problem of rehabilitation of steam power plants a very comprehensive, concise summation. I should like, however, to stress three points which have been indicated in the paper.

1. The effect of an existing transmission system on the problem of rehabilitation. The history of development of power systems has very often been one in which as the load developed newer and larger plants were built at various points on the systems, the old ones being left to struggle along as best they could. The transmission system has naturally in all that time kept pace with the growth, that is, the transmission system was developed around the various generating point sites; it is of course the only way it could develop. As the territorial expansion of a system slowed up, and this is true of many of them today, the situation that the engineer was confronted with was one in which a number of the lines built in previous years had gradually ceased to function because the location of the newer stations was such as to favor some other lines. An analysis of the economics of rehabilitating some of the old sites in any case of that sort would very often go far astray unless full weight were given to the combined plant and transmission-line set-up. It will often be found that it is economically desirable and feasible to rehabilitate a plant even though the thermal economy derived from it is not as high as that possible from some other plant for the simple reason that its rehabilitation would put to use a transmission line that might represent two or three million dollars worth of investment.

2. As pointed out by Dr. Hirshfeld, rehabilitation will generally result in radical reduction in investment cost per unit of capacity. It is to be noted that the generating station, through the possibility it offers for rehabilitation, is one of the few places on the electric power system that affords the possibility of a sharp cut in the cost of facilities per kilowatt to be served.

3. On the question of ground area, cubical contents, and related questions which Dr. Hirshfeld brings up as necessary to be settled in the light of the policy to be followed with regard to rehabilitation, I should like to state that I have seen cases where not only would the original design limits with regard to space and area, etc., prove inadequate when rehabilitation time came around but very often showed their inadequacy before the design had progressed to completion. It would seem that this particular question of design could certainly be treated more liberally than would be warranted by a mere consideration of figures produced with the aid of an engineer's scale and slide rule.

Application of Induction Regulators to Distribution Networks

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Synopsis.—This paper considers in a general way the application of automatic induction voltage regulators to network distribution systems. A discussion is given of the usual methods of applying both single- and three-phase induction regulators and their relative merits are considered.

The latter part of the paper takes up various methods that may be used to obtain successful operation when automatic induction regulators are operated on parallel feeders.

* * * * *

ABOUT 80 per cent of the network systems now in operation use induction regulators to control the voltage of the network.

Over 75 per cent of these apply separate regulators to the individual feeders though under certain conditions there are some advantages in regulating the voltage on the bus rather than on the individual feeders. These conditions exist on a network system supplied from one station by feeders of the same voltage rating which carry the entire load supplied by the bus. Because of the interlacing and the fact that they feed into a common secondary system, the load carried by each feeder, particularly at the time of heavy system load, is generally well divided among them. Under these conditions, bus regulation will frequently give satisfactory voltage at the load. Furthermore bus regulation requires the minimum amount of space for regulating equipment and none of the problems involved in the operation of automatic regulators on parallel feeders is encountered.

However, the outstanding disadvantage of a bus regulator is that the entire network system would be without voltage regulation if anything should happen to the one bus regulator. Furthermore the advantages of this type of regulation are considerably minimized if any of the favorable conditions do not exist. For these reasons individual feeder regulators are used in the majority of cases.

REGULATOR APPLICATION

On a three-phase three-wire feeder, one three-phase regulator, two single-phase regulators or three single-phase regulators may be employed, while on a three-phase four-wire feeder, either three single-phase or one three-phase regulator may be used. Any of these will give satisfactory voltage conditions at the load if the bus voltage of each phase and the current carried by each line are balanced.

A three-phase regulator is usually connected to a feeder as shown in Fig. 1. The voltage in all three phases is varied an equal amount by any movement of the three-phase regulator. With the connections shown

in Fig. 1 the operation of the regulator is controlled by only certain phases of the feeder. For this reason the results obtained by the use of three-phase regulators are not entirely satisfactory when there is a serious unbalance of either voltage or current in the different phases of the feeder.

The action of a three-phase regulator is illustrated in Fig. 1A. The triangle ABC represents the voltage conditions existing at the station bus, while the triangle XYZ shows the regulated voltage. It may be seen from this that if the three-phase regulators in the different feeders supplying a network are not made to boost or buck the same amount at all times, an angular

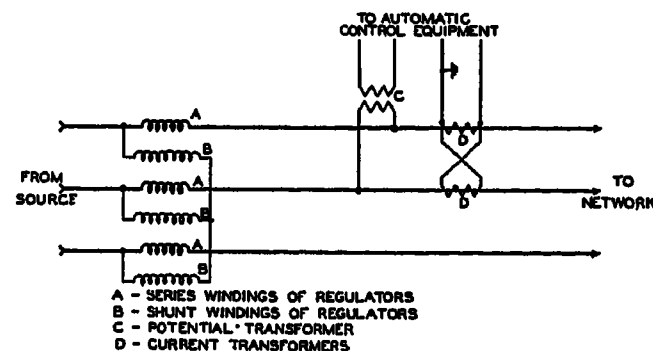


FIG. 1

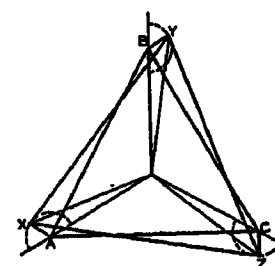


FIG. 1A

FIG. 1 AND 1A—VECTOR AND CONNECTION DIAGRAM OF THREE-PHASE INDUCTION REGULATOR

voltage displacement is introduced between the corresponding line to neutral and line to line voltages in the different feeders. With the first type of network protectors developed, this angular shift of voltage had the serious effect that it was liable to cause pumping, that is, periodic opening and closing of the network protectors. This action is fully explained in a paper by W. R. Bullard.² The possibility of network protectors pumping because of this angular voltage displacement has been eliminated in the latest type of protector by the

1. Both of the Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

2. Operating Requirements of the Automatic Network Relay, by W. R. Bullard, A. I. E. E. TRANS., Vol. XLV, 1926, p. 1203.

addition of the phasing relay.³ The voltage shift, however, still introduces some undesirable system conditions.

The usual connections used for two single-phase regulators on a three-phase feeder are shown in Fig. 2. With unbalanced voltage and current conditions in the feeder, this method will generally give closer regulation than one three-phase induction regulator, but still will not give correct regulation on all three phases.

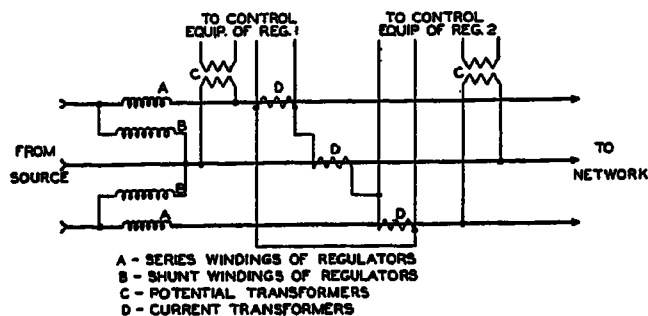


FIG. 2

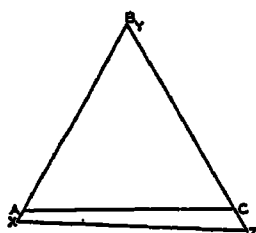


FIG. 2A

FIG. 2 AND 2A—VECTOR AND CONNECTION DIAGRAM OF TWO SINGLE-PHASE INDUCTION REGULATORS ON THREE-PHASE THREE-WIRE FEEDER

The action of two single-phase regulators on a three-phase feeder is illustrated in Fig. 2A. The triangle ABC again represents the voltage conditions at the bus, and XYZ shows the regulated voltage with the two regulators in somewhat different positions. The voltages added to or subtracted from the line voltages BA and BC are in phase with the line voltages at all times, and are simply varied in magnitude by the movement of the regulators. As a consequence, there can be no angular shift produced between these two voltages in the different feeders. However, the phase angle as well as the magnitude of the voltage in phase AC is changed by an unequal movement of the two regulators on the other phases, as is illustrated by the line XZ . It is entirely possible, therefore, to have an angular displacement of the voltages of this phase in different feeders, and such a shift could introduce the same trouble on the older type of network protectors as that caused by three-phase regulators. To avoid this difficulty, the companies using two regulators connected in open delta on network feeders have mechanically connected together the two regulators on the same feeder which prevents an angular shift of any of the voltages, but at the same time forces all phases of the feeder to accept the same amount of regulation.

If the feeders supplying the network are connected three-phase, four-wire and three single-phase regulators are used on each feeder, these regulators may be ap-

plied as shown in Fig. 3. The primary winding of each regulator is connected from line to neutral. Correct regulation from line to neutral can be obtained with the arrangement, no matter how unbalanced the currents and voltages of the feeder may be as long as the corrective factor required is within the range of the regulators.

As illustrated in Fig. 3A, the voltages added or subtracted by the action of the regulators are always in phase with their respective line to neutral voltages, and there is, therefore, a fixed phase relation between these voltages in the different feeders. The line to line voltages may be shifted in phase somewhat due to unequal action of the three regulators, but this has no effect on the voltages being considered since the high voltage sides of the network transformers will also be connected between the phase wires and neutral. It follows, therefore, that three regulators on a three-phase, four-wire system give correct voltage under any unbalanced conditions in the different phases.

Fig. 4 shows the connections used when three single-phase regulators are used on a three-phase, three-wire system. With this arrangement correct regulation will be obtained even though the voltages and currents of the feeder are unbalanced.

The action of the regulators is shown in Fig. 4A. Here again a phase angle shift of the voltage triangle is introduced by the regulators. An angular displacement between the corresponding line to line voltages in

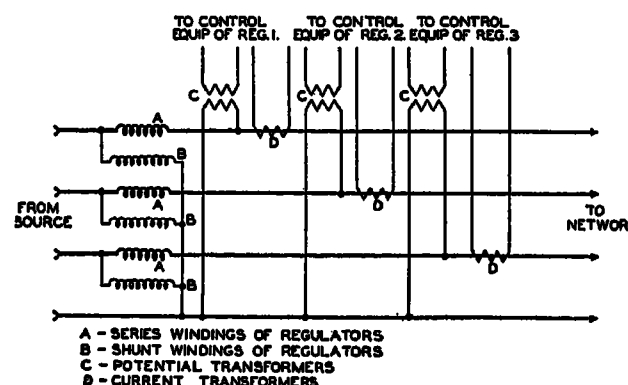


FIG. 3

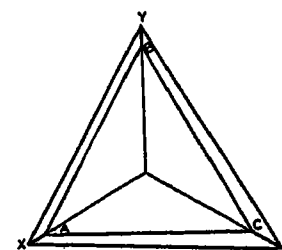


FIG. 3A

FIG. 3 AND 3A—VECTOR AND CONNECTION DIAGRAM OF THREE SINGLE-PHASE REGULATORS ON A THREE-PHASE FOUR-WIRE FEEDER

the different feeders can be avoided by mechanically connecting together the regulators in the corresponding phases in the different feeders.

A comparison of the relative first costs of the regulators for different feeder sizes has been worked out for each of the arrangements described, and the results are given in the curves of Fig. 5. In each case the line to line voltage of the feeder has been taken as 4000 and the proper regulators applied to give a regulation of 10

3. "The Network Relay," by J. S. Parsons, *Electric J.*, Dec. 1927.

per cent buck or boost. The curves in Fig. 5 have been made up for comparative purposes, and the differences in costs are expressed in per cent rather than in cost figures. The same thing has been done in working out the curves on comparative losses.

The three-phase regulator must have a 4000-volt

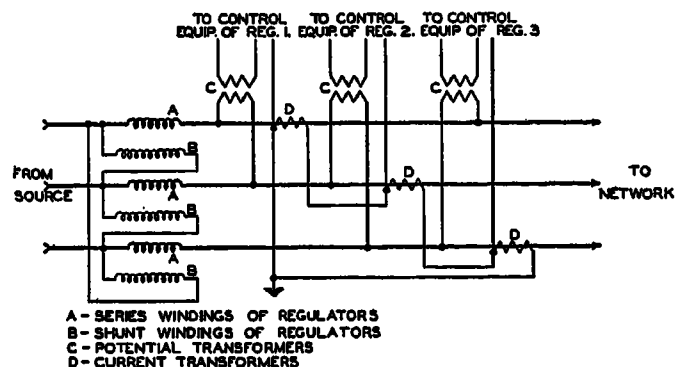


FIG. 4

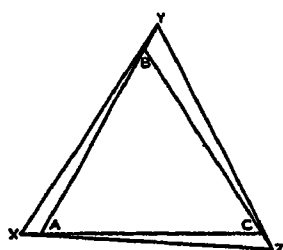


FIG. 4A

FIG. 4 AND 4A—VECTOR AND CONNECTION DIAGRAM OF THREE SINGLE-PHASE REGULATORS ON A THREE-PHASE THREE-WIRE FEEDER

rating for application on a 4000-volt feeder and must have a kv-a. rating of 10 per cent that of the line in order to give the ten per cent regulation. The costs of such regulators for different feeder capacities are shown as Curve D of Fig. 5.

A single-phase regulator used on a three-phase four-

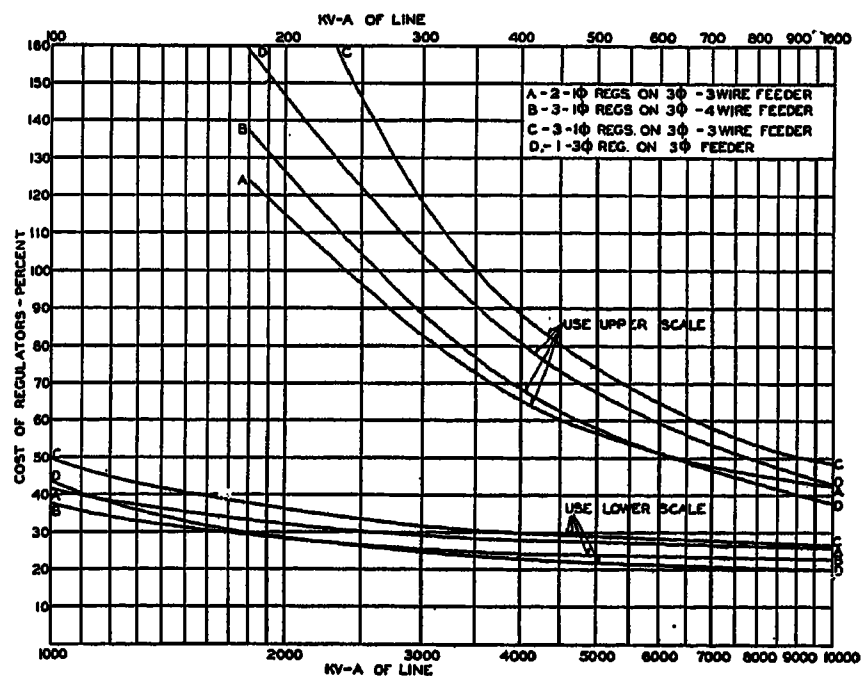


FIG. 5—COST COMPARISON REGULATORS FOR 4000-VOLT FEEDERS

wire feeder is designed for the line to neutral voltage, or in this case 2300 volts. The same total regulator capacity is required to give the range of 10 per cent above and below normal as in the case of the three-phase regulator, or in other words, each single-phase regulator has a rating of $3\frac{1}{3}$ per cent of the line kv-a.

The cost of three single-phase regulators for such a feeder, plotted in per cent against the line kv-a., is given in Curve B of Fig. 5.

The total regulator capacity required to give corresponding regulation is higher when three single-phase regulators are used on a three-phase three-wire system (Fig. 4) than if used on a three-phase four-wire system (Fig. 3). In order to obtain 10 per cent buck or boost of the line-to-line voltage, each single-phase regulator must be rated at 3.8 per cent of the feeder kv-a. The voltage rating of regulators applied in this manner is, of course, the line-to-line voltage. The cost of three such regulators for different feeder capacities is given in per cent in Curve C of Fig. 5.

Two regulators, connected in open delta, on a three-phase three-wire circuit must each have a rating of 5.77 per cent of the feeder kv-a., and must be designed for line-to-line voltage. The cost of the two regulators is plotted against feeder kv-a. in Curve A of Fig. 5.

The losses of each of these combinations of regula-

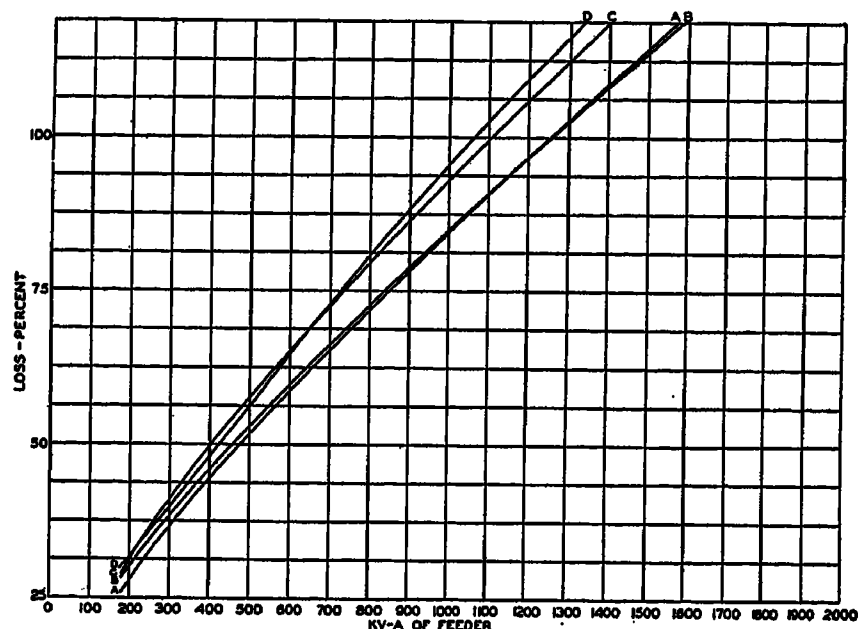


FIG. 6—LOSS COMPARISON REGULATORS FOR 4000-VOLT FEEDERS

tors, expressed in percentage, are shown in the four curves in Fig. 6. The curve letters used in Fig. 6 refer to the same regulator arrangements as the corresponding curves in Fig. 5.

The use of feeder voltages of 11 kv. and 13.2 kv. has become rather common on a-c. automatic network systems. When regulators are supplied on such feeders, it is possible to use high-voltage regulators connected to the feeder in the usual manner, or to use standard 2.4-kv. regulators with shunt and series transformers. The primary windings of the regulators are supplied through the shunt transformers, and the secondary windings of the regulators are connected into the feeder through the series transformers. The question of which type to use is essentially an economic one, and Fig. 7 shows the first cost of the two types. Curves A and B in Fig. 7 are for three-phase regulators, while Curves C and D are for single-phase regulators. The comparison is based on regulator ratings only.

The losses of the regulator combination using series

to shunt transformers are usually higher than for the standard high-voltage regulator except in small sizes. The floor space required for the outfit using the larger number of units will be the greater, but this arrangement gives the greater flexibility.⁴

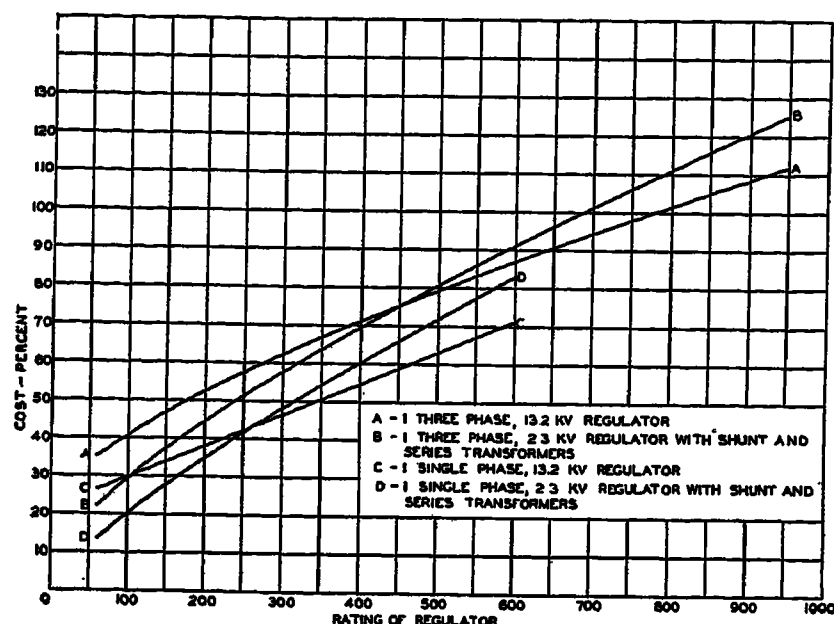


FIG. 7—COST COMPARISON REGULATORS FOR 13,200-VOLT FEEDERS

All of the cost curves have been based on automatic indoor regulators which have been the ones most commonly used up to the present time. The use of outdoor regulators has recently been increasing very rapidly, but a comparison of this type of regulator would show only minor modifications of the cost curves already given. It should also be noted that no allowance has been made in the cost curves for the omission of one set of automatic control equipment when two regulators operating in open delta are mechanically connected.

OPERATING PROBLEMS

A number of problems arises in the operation of regulators on the parallel feeders supplying a distribution network.

Fig. 11 clearly illustrates that a closed loop is formed by the feeders, the station bus, and the secondary system, and a voltage unbalance will tend to set up a circulating current in this loop. If the regulators are applied in the manner generally followed on the feeders of radial systems, and the line-drop compensators set in the usual manner, it is possible that regulator instability may be encountered. For example, if a small circulating current is set up, the current in one feeder is increased, while that in the other is decreased. The increased current in one feeder acts on the line-drop compensator to cause the regulator to further increase the voltage in this feeder, while in the other feeder the opposite action takes place. It can readily be seen that this may result in a cumulative action, one regulator going to the maximum boost position, the other turning to the maximum buck position.

The problem in brief, therefore, is to maintain satis-

4. "Regulators for Network Distribution Systems," by E. E. Lehr, *Electric J.L.*, July, 1925.

factory voltage at the load, and at the same time prevent unstable operation of the regulators.

PARALLEL OPERATION

The first and the most reliable means of operating regulators in parallel is by mechanical interconnection. This consists of a shaft connecting the operating mechanism of the regulators. One set of automatic accessories is used to control the several regulators so mechanically interconnected.

It is frequently inconvenient or impossible to mechanically interconnect regulators to operate in parallel, because of the necessary physical arrangement. Regulators to operate in parallel may even be located in different substations. In these circumstances, it has been considered necessary to use some form of electrical interconnection. The mechanical interconnection forces each feeder to have the same voltage, so that if the impedances of the feeders differ, they will not divide the load equally. This corresponds to substation bus regulation, but has the advantage that failure of one regulator does not affect the regulation of the other feeders. The two central regulators shown in Fig. 8 are 344-kv-a., 13,200-volt, three-phase, self-cooled induction regulators, mechanically interconnected and regulating the voltage of two parallel feeders.

One of the first schemes of electrical interconnection used is that shown in Fig. 9. This arrangement is usually referred to as cross-compensation. The diagram shows the circuit for controlling two single-phase induction regulators in open delta on a three-phase, three-wire system, the two regulators of each feeder being mechanically interconnected. The source of potential for the primary relay is the voltage transformer connected directly across its own feeder. The current

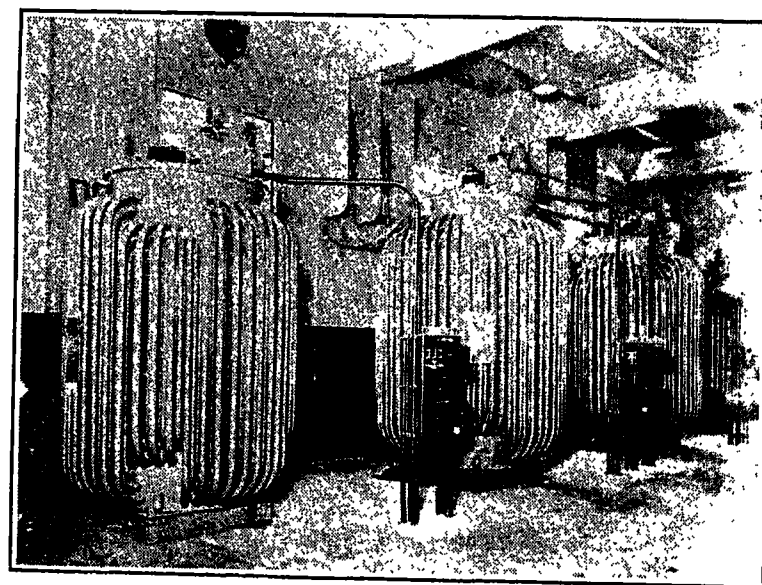


FIG. 8—THREE-PHASE 13,200-VOLT AUTOMATIC INDUCTION REGULATORS MECHANICALLY INTERCONNECTED

for line-drop compensation, however, is obtained from the current transformer of the adjacent feeder. Each compensator is set for its own feeder impedance. The action of the auxiliaries is described in the following paragraph.

With an increase of load, each feeder will take a portion of the increase inversely proportional to its impedance at the instant of increase. Thus the feeder of lowest impedance takes the greatest share of the added load. The tendency to increase the voltage of this feeder is not very great, because its compensator is set for low impedance, and the increase in current due to the additional load is small, since it is taken from the ad-

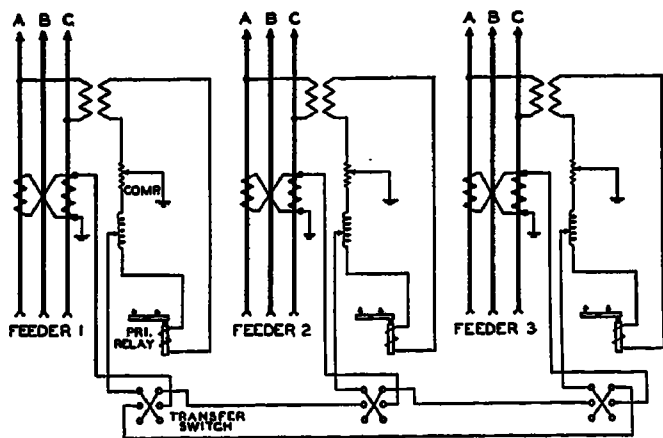


FIG. 9—REGULATORS ON PARALLEL FEEDERS WITH CROSS-COMPENSATION

jacent feeder. The feeder having the highest impedance has taken the smallest share of the added load at the instant of increase, but the tendency for the regulator to raise the voltage is greatest, because its compensator is set for high impedance and the current obtained from the adjacent lower impedance feeder is higher than its own current. The tendency of the regulator accessories is therefore such as to cause each feeder to take an equal share of the increase in load. This is one of the requisites of stable parallel operation.

This method of cross-compensation can only be successfully applied to feeders that have appreciable impedance, since the sensitivity of the control circuit to circulating or unbalanced current is dependent on the compensator setting. For example, assume a feeder with but 5 per cent impedance and the compensator set at 5 per cent. The usual contact setting of the primary relay is $\pm 1\frac{1}{2}$ per cent. Thus it would require a circulating current of 30 per cent full load to cause the primary relay to make contact and cause the regulators to restore balanced conditions. This cross-compensation scheme has been largely superseded by the standard method of connections as will be explained.

Fig. 10 illustrates a circuit developed to secure sensitivity to circulating current. The diagram shows only the control for only one regulator on each three-phase four-wire circuit. Two additional current transformers, CT_1 and CT_2 , on the parallel feeders are connected in series so that when the feeders are carrying the correct portion of the load, the secondary current of the current transformers simply circulates between the current transformers. If, however, the current in the feeders is unbalanced, twice the unbalanced current will flow through the compensators, since the current transformers have very high impedance to any current other than ratio primary current. The compensators are so

connected that a voltage is induced in the primary relay circuit so as to restore normal conditions.

The transformers CT_3 and CT_4 supply the current for line-drop compensation in the usual manner. For feeders of low impedance, the current transformer ratios are chosen so as to give a high compensator setting to secure sufficient sensitivity to circulating current. For example, for a 200-ampere feeder having 5 per cent impedance, the current transformer ratio for line-drop compensation would ordinarily be 200 to 5. As previously pointed out, a compensator setting of 5 per cent is not sufficient to secure satisfactory operation. In order to set the compensator at 10 per cent, a 400-to-5 current transformer would be used for line-drop compensation, and the 200-to-5 ratio for the current transformers used for the unbalanced current. It will be seen that this connection forces the feeders to carry current of approximately the same magnitude, or in a definite proportion.

This method has been satisfactorily used with three regulators solidly bussed on both power and load sides, maintaining a constant voltage on the regulated bus. The regulators perform as though they were mechanically connected by a somewhat flexible shaft, the flexibility being controlled by the closeness of the primary relay adjustment. The compensators, of course, are not used to obtain line-drop compensation but to limit the circulating current in this case and the current transformers CT_3 and CT_4 are omitted.

Another installation was made several years ago using the connections shown in Fig. 10 for two sets of

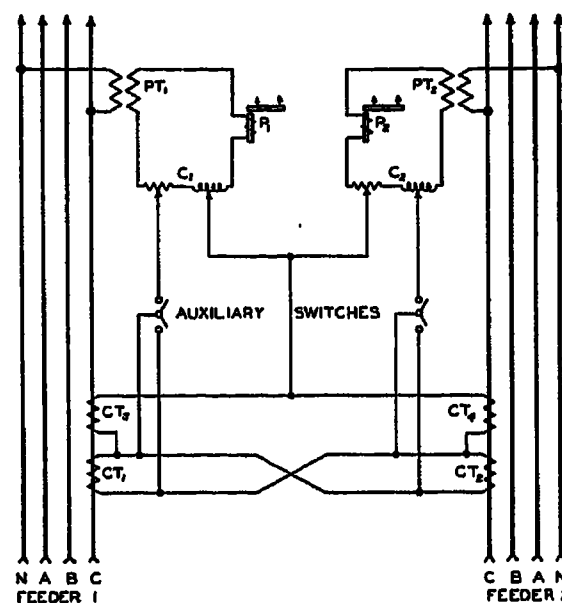


FIG. 10—CIRCUIT FOR LIMITING CIRCULATING CURRENT AND INCLUDING LINE-DROP COMPENSATION

three single-phase induction regulators on a three-phase four-wire circuit. These regulate two feeders supplying a bank of transformers connected in parallel on both high- and low-voltage sides. This installation has been operating very satisfactorily. The regulators are protected by thermal relays so that in case of failure of any of the auxiliaries to function, the breaker will automatically open the circuit. To date, however, there has

been no occasion for the breakers to open through the action of these relays.

All of the schemes described so far require mechanical or electrical interconnection. Where all regulators feeding the network are located in the same substation, there is no serious objection to electrical interconnection. However, as the size of the network increases new substations may be required. If electrical interconnection is employed, pilot wires must be used between the regulator circuits, which is objectional both from a cost and operating standpoint.

Induction regulators are now being applied to networks in many cases, using only the standard method of connection.

To secure satisfactory operation, certain precautions must be taken and the auxiliaries properly adjusted, and the loop impedance must be sufficiently high to permit an appreciable compensator setting. This has been proved by theory, tests, and actual field practise.

The two regulators shown in Fig. 11 controlling the

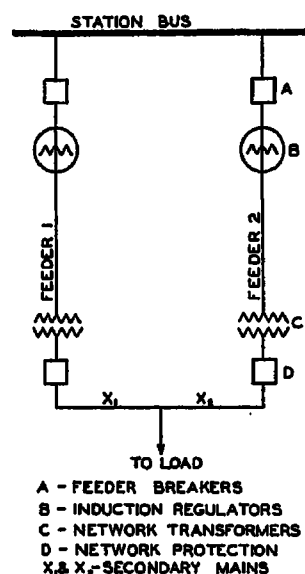


FIG. 11—SINGLE-LINE DIAGRAM OF SIMPLIFIED NETWORK SYSTEM

voltage of the feeders to the network transformers are connected in the standard way. If the compensators of each regulator are set for one-half the loop impedance, the regulator auxiliaries produce no restoring effort when the regulators are displaced from each other an equal amount from the normal position. If one regulator is manually displaced from the normal position by X per cent in the boost direction, a circulating current of $\frac{X}{Z}$ will flow where Z is the loop impedance in per cent.

The voltage which acts on the primary relay of the regulator displaced is the regulated voltage $1 + X$ less the voltage of the compensator, which in this case is $\frac{X}{Z} \times \frac{Z}{2} = \frac{X}{2}$. If the regulator is released at

this point, it will return to the normal position, since the primary relay voltage is higher than normal. However, suppose the regulator is held displaced and the action of regulator No. 2 examined. The primary relay voltage

of No. 2 regulator will then be $1 + \frac{X}{2}$ and it will

start toward the buck position. When it reaches X per cent from the normal position in the buck direction,

the circulating current will then be $\frac{2X}{Z}$. The pri-

mary relay voltage of No. 1 regulator is the normal voltage plus the boosted voltage less the product of the circulating current and the compensator setting. The product of the circulating current and the compensator setting is equal to the boosted voltage, *i. e.*,

$$\frac{2X}{Z} \times \frac{Z}{2} = X.$$

In other words, the compensation is equal to the voltage above normal caused by the action of regulator No. 1. Since the voltage of the compensator and the above normal feeder voltage are in opposition in the primary relay circuit, normal voltage is applied to the primary relay and no action takes place. The voltage of No. 2 primary relay is the normal voltage less the voltage below normal plus the compensator voltage. The resultant again gives normal voltage applied to the primary relay.

It should now be noted that if the compensators are set for anything less than one-half the loop impedance, a restoring effort will result as the compensation is less than the voltage above normal caused by regulator No. 1. The primary relay voltage therefore is greater than normal and will tend to cause regulator to return to normal position. If, however, the compensators are set for more than one-half the loop impedance, the compensation will be greater than the voltage above normal caused by regulator No. 1. Thus the primary relay voltage is less than normal and regulator No. 1 will not tend to return to the normal position but will go to full boost position. The opposite action takes place at regulator No. 2 and it will go to full buck position.

Fig. 11 is a single-line diagram of a typical network. The load is shifted from the middle point, as shown, to a point adjacent to the network protector in order to check the stability of operation with different compensator settings. This is accomplished by making X_1 equal to zero and X_2 equal to the impedance of the secondary mains. If the compensators are set to maintain a constant voltage at the load instability will result, since the action of the load current on the compensator of regulator No. 1 is greater than the voltage increase caused by the regulator.

Table I has been prepared from calculations showing the load voltage and division of load current for different compensator settings with a concentrated load, of 100 per cent at 80 per cent power factor with X_1 equal to zero, and varying values of X_2 . The table is based on a reactive circuit neglecting resistance, and the power factors given are based on the load voltage. The location of the load chosen in making up this table repre-

TABLE I

Compensator setting Per cent	Load voltage Per cent	Current		Power-factor		Reactance		X_2
		FDR. No. 1	FDR. No. 2	FDR. No. 1	FDR. No. 2	FDR. No. 1	FDR. No. 2	
0	96	66.7	33.3	80	80	10	10	10
9	99.5	76.5	27.2	70	98	10	10	10
8	99.0	74.0	28.0	72	95	10	10	10
5	97.7	70.0	30.6	76	87	10	10	10
0	96.4	60.0	40.0	80	80	10	10	5
9	99.5	70.3	33.1	68	97	10	10	5
8	99.1	67.6	34.0	71	94	10	10	5
5	98.0	62.5	37.6	77	85	10	10	5
0	97	50	50	80	80	10	10	0
9	99.7	50	50	80	80	10	10	0
8	99.4	50	50	80	80	10	10	0
	98.5	50	50	80	80	10	10	0
*	99.6	60	40	80	80	10	10	5

*Compensator feeder No. 1 set at 9 per cent and compensator feeder No. 2 set at 13.5 per cent.

sents the most severe condition for obtaining regulator stability. A typical example of such a condition is at start of network operation when one building is supplied by two feeders and two network transformers. The table shows the action, both with and without reactance between network transformers. The table has been made only for single-phase regulators.

It will be noted that as the compensator setting is decreased for a given system condition, there is more nearly an equal division of the reactive component of the load. Better load voltage and division of the load current also prevail when the reactance of the secondary mains is small in comparison to the feeder reactance.

Tests have been made that fully verify all of the results given in the table. Actual operating experience also shows that stable operation of single-phase regulators is obtained and satisfactory voltage maintained in secondary system if care is taken in setting of the relays and compensators.⁵

The operation of three-phase regulators on network feeders differs from single-phase regulators because of the manner in which they change the feeder voltage, (Fig. 1A). The regulated voltage of all the parallel feeders from the same bus will have the same magnitude and phase relation only when the rotors of the regulators have the same relative position. An angular difference in the rotor positions will result in a voltage tending to circulate current. The phase and magnitude of this voltage will depend upon the relative positions of the rotors.

The voltage causing circulating current of two three-phase regulators in parallel, one of which has its regu-

lator voltage BY (Fig. 1A) at slightly less than 90 deg. from OB and the other slightly more than 90 deg. from OB , will be approximately in phase with the voltage OB . Also any change in magnitude of the voltage causing circulating current will change the regulated voltage OY , applied to the primary relay, by approximately the same amount.

However, with the two regulators a few degrees apart but in such a position that voltage BY is nearly in phase with OB , the conditions are entirely different. In this case, although the voltage tending to circulate current may be of the same magnitude as that in the preceding case, it is nearly at right angles to the voltage OB .

Furthermore, a change in magnitude of the voltage causing circulating current has no appreciable effect on the regulated voltage applied to the primary relay. Thus the voltage tending to set up a circulating current and therefore the circulating current itself can have a phase relation from practically zero to 180 deg. with voltage OB . Consequently, satisfactory operation of three-phase regulators in parallel using standard connections may be obtained only when the loop impedance is comparatively high.

The use of electrical interconnection becomes difficult when three-phase regulators are used because of the varying phase relation of the voltage causing circulating current. Mechanical interconnection of the regulators on the different feeders, however, will prove entirely satisfactory. The inherent phase displacement of the regulated voltage by three-phase regulators may be overcome by the use of two three-phase regulators with their secondaries connected in series in such a way that the vector sum of their secondary voltage will always be in phase with the line to neutral voltage. The operation then becomes the same as single-phase regulators.

Summarizing, the type of induction regulators to be applied to network feeders depends largely on the network and feeder characteristics. The feeders and network forming the loop between the regulators may be classed as low, moderate, and high impedance. It is desirable to interconnect mechanically both single- and three-phase regulators on low impedance loops. If single-phase regulators are used on low impedance loops electrical interconnection as shown in Fig. 10 may be successfully used. On moderate impedance loops single-phase regulators may usually be successfully operated without any interconnection while three-phase regulators should be mechanically interconnected. Either single-phase or three-phase regulators will operate satisfactorily on a high impedance loop using the standard operating control circuit.

5. *Operating Experience with the Low-Voltage A-C. Network in Cincinnati*, by F. E. Pinckard, A. I. E. E. Quarterly TRANS., Vol. 47, July, 1929.

The Electrification of the Mexican Railway

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Synopsis.—The Mexican Railway Company, Ltd., locally known as Ferrocarril Mexicano, was the first railway built in Mexico, having been opened to traffic January 1, 1873. The main line runs between Mexico City and Vera Cruz and is 264 mi. in length. There are six branch lines which increase the route miles to a total of 482. The most difficult portion of the line consists of 19 mi. of 4.7 per cent grade between Encinar and Boca del Monte where the table-land is reached.

In 1921, when the road was returned to its owners, following five years of government operation, the property was found to be in an unsatisfactory condition, with operating expenses more than doubled, thereby increasing the operating ratio from 0.51 in 1914 to 0.79 in 1920. Higher wages and new working agreements were largely responsible and continued to become more difficult. The mountain division had about reached its maximum capacity with the existing equipment, making it necessary to consider improvements.

A study of the operating costs of this section was made in 1921 from which it was apparent that the electrification of that section would readily relieve the congestion and make it possible to more than double the capacity of the line and at the same time accomplish a yearly saving of \$523,000 in operating expense. The electrification was estimated to cost \$2,420,000, thus indicating a return of

21 per cent on the gross investment including electric locomotives, in addition to the increased capacity and many other advantages.

Construction work was started in January 1923 and electrical operation between Orizaba and Esperanza was complete in January 1925. The total cost for the 29 mi. section was \$2,427,480.00. Internal disturbances delayed the work several months and reduced the traffic greatly. In March and April 1928 the traffic becomes comparable with that of September and October 1921, for which period the actual traffic records and operating costs for steam operation had been used as a basis for comparison with the estimated cost of an equal traffic with electrical operation.

A comparison of actual operating costs of items affected by electrification for the two periods showed that 10 electric locomotives had hauled 36 per cent greater tonnage in 40 per cent less train hours than had 25 steam locomotives and at 50 per cent of the cost for items affected. When the figures were properly adjusted to compensate for increased tonnage and higher wages the saving indicated was at the rate of \$663,348 per year, a return of 26 per cent on the total cost of the electrification.

In the meantime the general results had been so satisfactory that the electrification was extended 35 mi. south to Paso del Macho, making a total of 64 mi. at a cost of \$3,606,937.00.

THE electrification of the Mexican Railway (Ferrocarril Mexicano) is of special interest as being the first undertaking of this nature carried out in old Mexico. The initial study of the problems involved was made in 1921 and a contract was signed for the construction work and for the electrical equipment in 1922. The work was completed and electrical operation started in 1925.

The operation has been so conspicuously successful that it would now seem to be of general interest to describe many of the details of construction and to give such operating data as are available.

The main line of the Mexican Railway extends from Mexico City to the Gulf Coast at Vera Cruz and is 264 mi. in length. There are six branch lines, making the total length:

TABLE I
STANDARD GAGE (4 FT. 8½ IN.)

	Miles
Vera Cruz to Mexico.....	264
Apizaco to Puebla.....	29
Ometusco to Pachuca.....	29
Pachuca to Ixmiquilpan.....	51
	373
Sidings and Second Track.....	74
	447
NARROW GAGE	
Huajuapam Branch (3 ft.).....	56
Zacatlan Branch (2 ft. 6 in.).....	33
Huatusco Branch (2 ft.).....	20
	109
Total mileage.....	556

1. General Electric Co., Schenectady, N. Y.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

From Mexico to Esperanza the line follows the general contour of the plateau, resulting in frequent reversal of gradients, but none exceeding 1.5 per cent. The elevation at the terminus in Mexico City is 7346 ft. The highest point on the line is near Acocotla, 95 mi. from Mexico, at an elevation of 8320 ft., a rise of about 1000 ft. From this point to Esperanza, a distance of 58 mi., the drop is 240 ft. with the surface undulating as before.

At Boca del Monte (The Mouth of the Mountain), 2.8 mi. west of Esperanza, the plateau ends suddenly and the descent for the following 19.0 mi. to Encinar is very rapid.

At Santa Rosa the line enters the valley of the Rio Blanca and the grade becomes normal on to Orizaba.

From Orizaba to Paso del Macho the drop is considerable though much less rapid than that just described. In the 35 mi. there is a descent of 2466 ft. There are some comparatively long sections of tangent track, and the curves, except in the loop on the Metla Baranca, are not unusually numerous or seriously sharp. Fig. 1 shows a condensed profile of the electrified line.

The section from Paso del Macho to Vera Cruz, 48 mi. in length, is a gradual descent from an elevation of 1560 ft. to sea level, the ruling gradient being approximately 1.7 per cent and the alinement normal.

The promotion, the construction, and the operation of this road, the first to be built in Mexico, have all been in close synchronism with the interesting and tumultuous history of the country. The original charter was obtained in August 1855, but it was 18 years later, or in January 1873, that the road was formally opened to through traffic.

With the comparatively settled conditions which gradually came about with the ascendancy of Porfirio Diaz as President, the property became more prosperous and before the beginning of the disturbance leading to his abdication had been brought into splendid con-

The unsettled conditions that had existed in the country for the preceding 10 years and the taking over of the railroad by the Government between 1914 and 1920 rendered the records for any of this entire period unsuitable for forming a basis for the usual method of

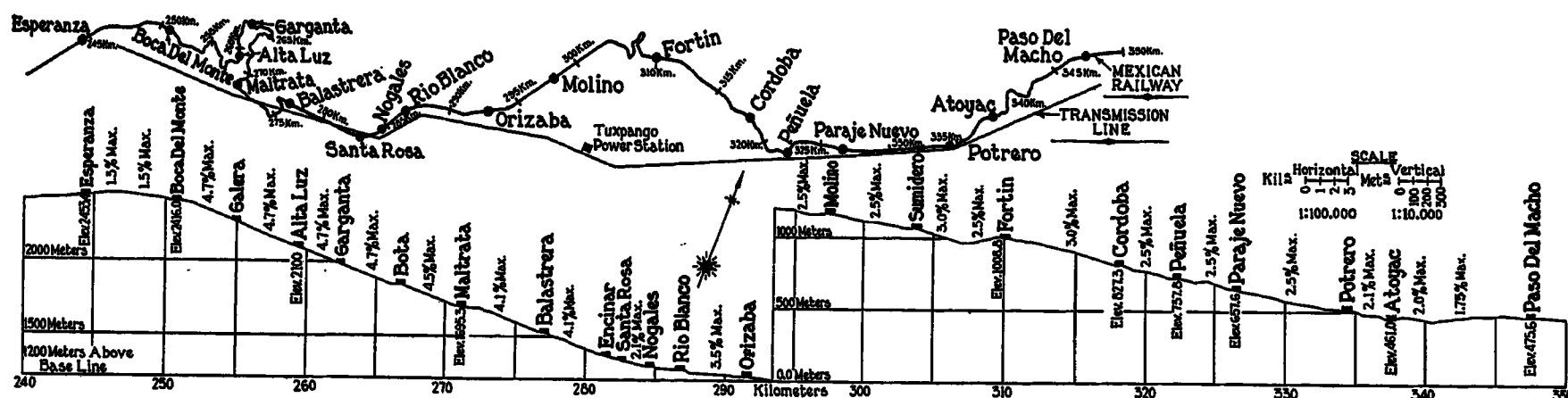


FIG. 1—PLAN AND CONDENSED PROFILE FROM ESPERANZA TO PASO DEL MACHO, ELECTRIFIED SECTION OF MEXICAN RAILWAY

dition. However, the revolution of 1910 suddenly brought an end to this prosperity and resulted in the road being taken from its owners for operation by the new Government in November 1914, under which control it remained until August 1916 when it was returned. It was again seized in April 1917 and held until June 1920.

When the property was returned to the owners, the line and equipment were found to be in very poor condition as practically no new apparatus or supplies had been purchased and the stores had been depleted. When the owners took charge of the road in 1920, many of the locomotives and cars were found to be in an inoperative condition with little material or supplies on hand with which to make repairs. New difficulties were also encountered in the nature of strikes which added greatly to the already difficult task of handling the increasing traffic.

In the fall of 1921, the business on the railway had grown so that it became very difficult to get the traffic over the mountain division from Orizaba to Esperanza which had always been the proverbial bottle neck. On October 25 a total of 14 trains, two of which were passenger, an aggregate of 4648 tons, was taken up the mountain, establishing a record for the division and indicating that the economic capacity of the single track line with existing type of motive power had been reached.

In November 1921 a study of the mountain division was begun for the purpose of determining the results that might be expected from the electrification of this congested district. About two months were spent in looking over the line and equipment, studying the conditions and securing operating data and costs. An equal time was required to analyze these data, estimate the cost of electrification, the savings in operating expenses that would result, and to prepare a report which was submitted in April 1922.

estimating the traffic that might reasonably be expected over the line for the following years.

Operating expenses had also been abnormally affected during the interval by substantial increase in wages, as well as by unusually expensive working agreements insisted on by newly formed labor organizations.

The semi-annual reports of the Mexican Railway for the six months ending December 31, 1920, the first period of operation after the return of the property by the Government, compared with a similar period of 1913, the last six months of operation by the owners prior to Government operation, for which the records were available, indicates increased costs as follows:

TABLE II

	1913	1920	Increase	
			Amount	Ratio
Maint. of way and structures.	\$195,755	\$379,652	\$183,897	1.94
Maintenance of equipment....	245,607	625,256	389,650	2.65
Conducting transportation....	720,148	1,563,682	843,485	2.17
General expense.....	105,120	199,760	94,640	1.90
Total operating expenses.....	\$1,256,630	\$2,768,350	\$1,511,672	2.20
Gross receipts.....	2,484,018	3,504,847	1,020,829	1.41
Net receipts.....	1,227,388	736,497	490,891	.61
Operating ratio.....	.51	.79	..	..

The comparative costs of the items that would be most directly affected by electrification for the above period were:

	1913	1920	Increase	
			Amount	Ratio
Repairs to locomotives.....	\$ 88,875	\$280,463	\$191,588	3.15
Enginemen and roundhouse...	72,931	236,673	163,742	3.24
Fuel for locomotives.....	244,202	359,071	114,869	1.45
Train service.....	80,295	200,008	119,713	2.49
Total.....	\$486,303	\$1,076,215	\$589,912	2.21

An analysis of the above comparative cost indicated that the motive power in use on the system should receive careful consideration.

The management of the railway suggested that the months of September and October 1921 should be taken as a basis for the study, since the traffic conditions and operating costs during that period were more representative of anticipated future conditions than any other period for which records were available.

The mountain district constituting the line between Orizaba and Esperanza, a distance of 29.5 mi., was then operated as a separate district and accurate operating expenses and statistics for steam operation were readily available for comparison with corresponding estimated costs of electrical operation.

The line between Orizaba and Paso del Macho was also included in the original study but since this was operated with the remainder of the line on into Vera Cruz, and the result of electrification could not be so definitely determined until an exact schedule of operation had been decided upon, only an approximate estimate was made for this section.

Of the 29.5 mi. between Orizaba and Esperanza, the 19 mi. between Encinar and Boca del Monte, which had been given careful consideration in the original survey, again became the determining factor relative to motive power. The actual rise in the 19 mi. is approximately 3500 ft., equal to an uncompensated grade of 3.5 per cent. With the exception of the first 2.5 mi. of this heavy grade just out of Encinar there is practically no tangent track, but continuously reversing curves, many of which are on a radius of 351 ft., equivalent to 16.5 deg.

In locating the line, it was apparently intended to keep the uncompensated grade at a maximum not to exceed 4 per cent and the maximum curve at 16.5 deg. During the study, it was learned that some new consolidation type locomotives that had been recently purchased and were temporarily being used on this division had failed to handle satisfactorily the weight of train they had been calculated to handle on the heavy grade.

The above engines were expected to be capable of taking a trailing load of 250 tons up the mountain grade. In practise, it was found that it was not practicable for them to take more than 175 tons, which represents a coefficient of adhesion of approximately 20 per cent on a grade of 4.7 per cent. Since the profile did not indicate a grade in excess of 4 per cent, or curvature greater than 16.5 deg. at any point, an investigation was made which indicated that there were certain points on the line where the engines stalled from the slipping of drivers and as there was no indication that the condition of the rails at this point was responsible an engineer was sent to check the grade.

It was found that short sections of track from 300 to 500 ft. in length showed actual uncompensated grades as high as 4.4 per cent which when properly compensated for curvature would make the maximum grade 5.24 per cent. The average uncompensated grade for the 1.24 mi. which represented the section of greatest

difficulty, was found to be 3.95 per cent, which when compensated for 16.5 deg. curvature at the rate of 0.90 lb. per deg. is equivalent to a grade of 4.7 per cent. Accordingly, this was taken to be the ruling grade for the division in the specifications for electric motive power.

The average weight of the passenger trains over the road was 215 tons, but these trains varied from 165 to 350 tons.

The steam locomotives that had generally been used for handling both freight and passenger trains on this division consisted of 32 four-cylinder Fairlie engines, of English build. These engines were designed especially for mountain service, having pack-saddle type tanks for fuel oil and water over a double-ended boiler which was mounted on two 3-axle swivel trucks, all the weight being on the drivers.

The engines had the appearance of two 3-axle switching locomotives coupled with cab ends together.

The fire-box was in the middle of the engines and contained two oil burners, the cab being over this central portion and the engineer located on one side of the boiler with the fireman on the opposite side. The engines ran equally well in either direction, and having a comparatively short rigid wheel base with all weight on the drivers at once deprived the electric locomotive of three of its usually boasted advantages.

The 32 engines were all of the same general type but of variable ages and weights as follows:

5 weighing, with full tanks.....	167,428 lb.
12 weighing, with full tanks.....	216,540
10 weighing, with full tanks.....	221,000
2 weighing, with full tanks.....	267,885
3 weighing, with full tanks.....	305,835

The first five of the above engines were not being used at the time, as ten new locomotives of the consolidation type had just been received and some of these were being substituted temporarily.

The weight of these new locomotives was as follows:

Weight on drivers.....	170,540 lb.
Weight on guiding axles.....	21,952
Weight of tender loaded.....	119,775
Total.....	312,267 lb.

During the months of September and October 1921 there had been taken over the division a total of 474 trains south bound, with an aggregate tonnage of 108,749 gross metric tons, and 622 trains with aggregate gross metric tonnage of 197,220, north bound. The total hours of elapsed time, or the hours for which the engine and train crews were paid between Orizaba and Boca del Monte where the helper locomotives on the freight trains were usually left off, were 1574 for the south bound and 2756 for the north bound traffic, making the average times for each train over the 25.4 mi.:

	South bound	North bound
Running.....	2 ft. 30 in.	3 ft. 39 in.
Delayed.....	0 ft. 49 in.	45 in.
Elapsed.....	3 ft. 19 in.	4 ft. 25 in.

This represented an average schedule speed of 7.66 mi. per hr., and 5.7 mi. per hr. respectively for the south bound and north bound trains, and an average delay of 47.4 min. per train or 25 per cent of the running time per train.

Practically all freight trains, and most of the passenger trains, required two engines. In the case of the passenger trains, both Fairlie engines were placed at the head of the train with a box-car between and with the freight trains an engine was placed at each end.

The average weight of the trains up grade was 317 metric tons or 350 U. S. tons. The down-grade tons were considerably less, as almost two-thirds of the traffic was north bound.

The average wage of the enginemen and trainmen on the Mexican Railway at the time was approximately as follows, based on an 8-hour day or 100 mi.:

	Pesos per day	Dollars per day
Engineers.....	12.00	\$6.00
Firemen.....	6.00	3.00
Conductors.....	11.00	5.50
Brakemen.....	5.28	2.69

The operating data and actual costs of the steam operation for the months of September and October 1921, were taken as a basis for estimating the saving that might be expected to result from the electrification of the Orizaba-Esperanza district.

Only the items of operating costs which would be most vitally affected were considered. The estimate as submitted in the report follows:

TABLE III

	Steam	Electric	Saving	Ratio steam to electric
Wages of enginemen.....	\$108,892	\$ 31,354	\$76,538	3.44
Wages of trainmen.....	85,290	23,191	62,099	3.68
Fuel and power.....	221,790	150,000	71,790	1.48
Repairs to locomotives.....	355,248	51,111	304,157	6.95
Enginehouse expense.....	20,946	5,841	15,105	3.57
Lubricants.....	16,656	2,921	13,735	5.70
Substation oper. and maint...	..	11,750	..	..
Maint. distributing system...	..	9,625	..	..
Total.....	\$808,822	\$285,793	\$523,029	2.82

The estimated cost of the electrification as submitted was:

10-150-ton electric locomotive units..	\$1,420,000
1-6000-kw. substation.....	350,000
30-Route miles distributing system...	430,000
Engineering and contingencies....	220,000
Total gross capital investment..	\$2,420,000

The report accordingly indicated a probable saving of \$523,029 per year by the expenditure of approximately \$2,420,000, or a return of slightly more than 21 per cent on the gross investment which included electric locomotives.

A similar study of the line between Orizaba and Paso del Macho was made at the same time, but as the savings that seemed probable were sufficient for a return only about half that of the Orizaba-Esperanza district, the report recommended that only the latter be undertaken in the beginning.

After a very careful examination of the report by the operating department of the railway, it was approved and recommended to the board of directors.

In October 1922 a contract was made for the required equipment and materials including the general supervision of the installation.

Actual work on the ground was begun in January 1923 and the work was completed and all trains were being hauled electrically by January 1925.

Just when the construction work had been fully organized and got well under way it was almost entirely stopped from the middle of December 1923 to May 1924 by the rebellion which occurred at that time. This interruption caused several months' delay and considerably increased the cost of the work.

The work was done almost entirely with native labor which had to be trained for the work. Three supervising engineers were placed in direct charge of the distribution, the substation, and the locomotives respectively, reporting to the resident engineer of the railway company, in cooperation with the general engineer of the contractor.

THE DISTRIBUTION SYSTEM

The simple catenary system, with double 4/0 trolley on the main line and single 4/0 trolley in yards and passing tracks, similar to that used on the C., M., St. P. & P., was adopted. Concrete poles were first selected for the supporting structure but it was found that several hundred old 30-ft., 82-lb. rails which had been replaced were on hand and that there was no market for these where the price offered would justify handling and transportation charges.

Some sample poles were made up from these rails by electric welding and tested for deflection and breaking strains which resulted in a decision to use these as far as the rails would supply the demand.

Of a total of 1920 poles made, 405 were concrete costing \$45.52 each and 1515 were made from old rails costing \$34.00 each. Figs. 2, 3, 4, 5, and 6 show both types of poles and typical examples of the overhead construction. Most of this work was done by contract, the unit price being fixed after sufficient experience had demonstrated a fair price. Bracket construction was used where possible, except where the poles supported feeder wires and it was desirable to avoid crossing these over the tracks too often. In such cases, as between

Boca del Monte and Alta Luz, the feeder cables were kept on the upper side of the track by having the poles continuous on that side, irrespective of the curves,



FIG. 2—OVERHEAD LINE IN NOGALES STATION SHOWING SPAN CONSTRUCTION WITH CONCRETE POLES

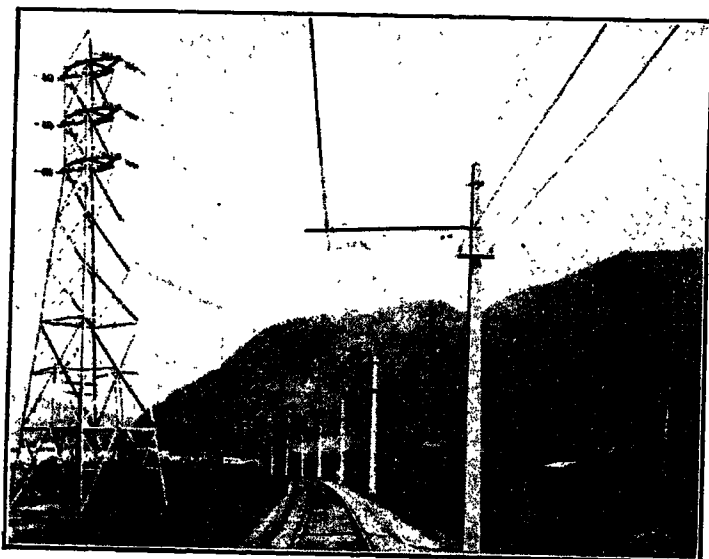


FIG. 3—100,000- AND 42,000-VOLT TRANSMISSION LINES CROSSING RAILROAD TRACKS

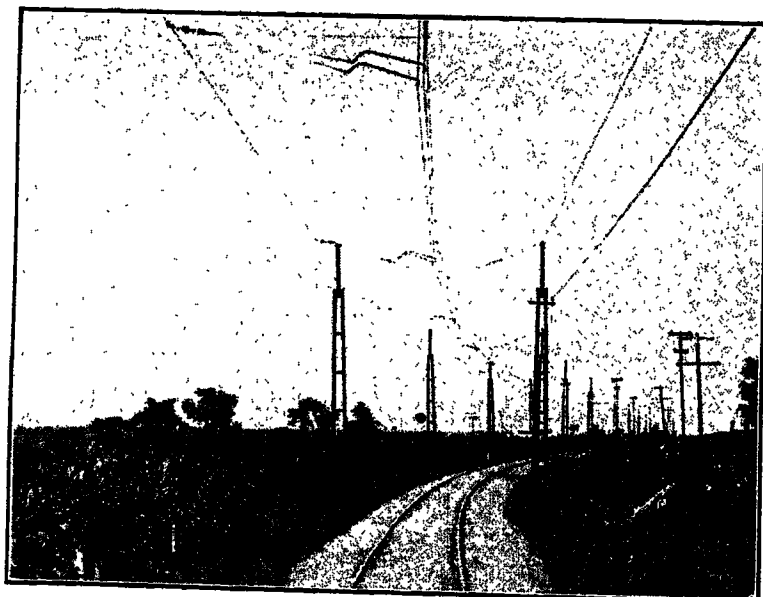


FIG. 4—OVERHEAD CONSTRUCTION ON CURVE JUST BELOW CORDOBA

thus using cross-span supports where the curves were outward from the upper side of the slope. This also prevented interference with the magnificent view from the car windows overlooking the valley.

In addition to the two 4/0 trolley wires two 500,000-cir. mil positive feeders and one 4/0 negative feeder cable were installed from Orizaba to Boca del Monte. The feeders were carried on separate poles at 4 points where the railway made long loops. The advantage thus gained was the reduction of feeder length from 29.5 mi. to 20.4 mi. The single substation for the 29.5 mi. was located near Maltrata and was almost an equal distance from each end of the feeder circuit, 10.2 mi. in length on either end. Only a single 500,000-cir. mil feeder was used between Boca del Monte and Esperanza as the grade here was comparatively light.

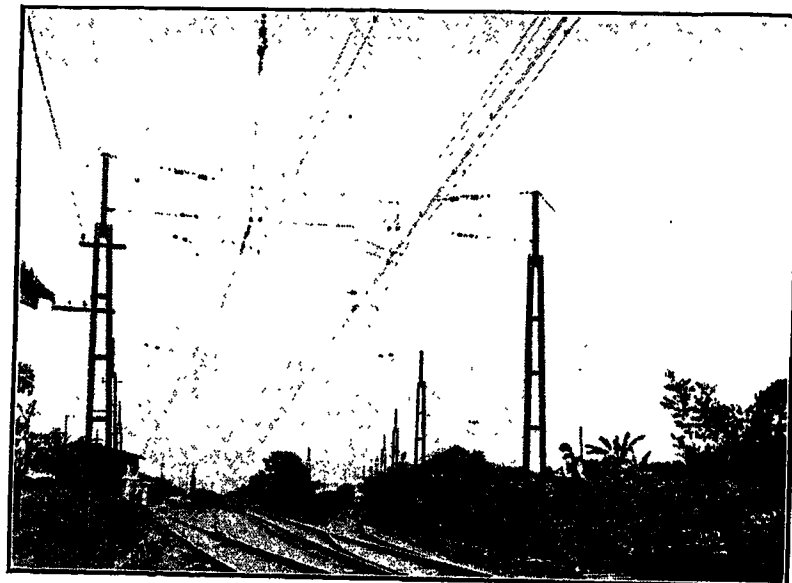


FIG. 5—OVERHEAD CONSTRUCTION AT ENTRANCE TO PARAGE NUEVO YARD

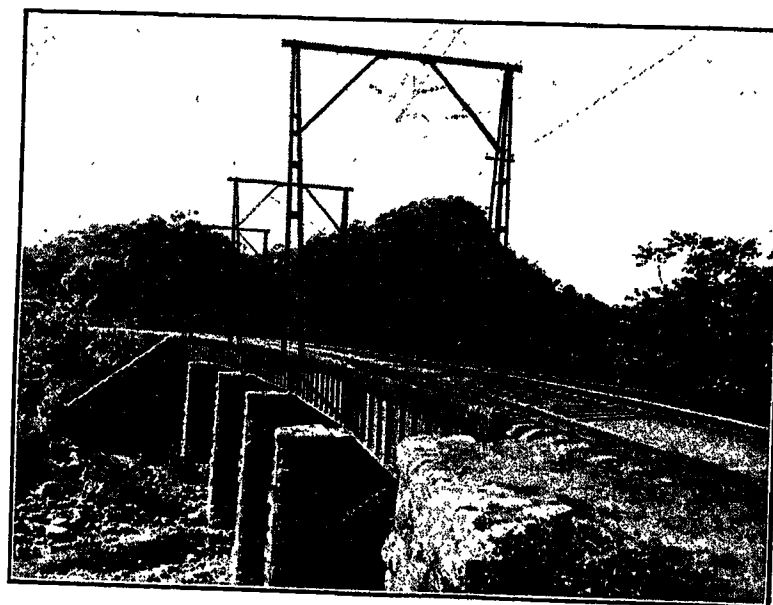


FIG. 6—TYPICAL OVERHEAD CONSTRUCTION ON BRIDGE AT RIO SECO

A similar feeder was used from the substation to the middle of the Bota loop, making it unnecessary to install any feeders along the railway between Bota and Alta Luz where the curvature was greatest, since this loop was fed from both ends making the equivalent of a double track circuit.

The voltage drop over the line between Orizaba and Esperanza with a 665-ton trailing freight train, also a 325-ton passenger train, is shown in Fig. 7. The drop up the grade with the heavier train was a maximum of

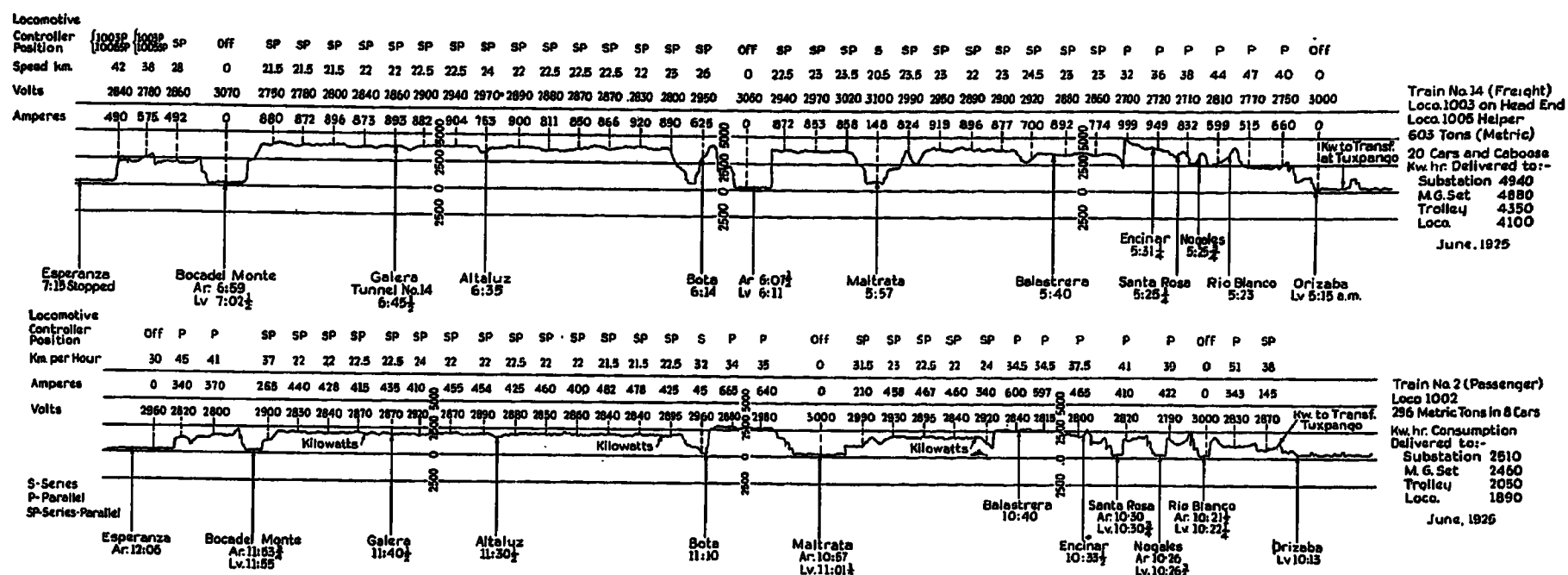


FIG. 7—TYPICAL KILOWATT CURVE WITH VOLT AND AMPERE READING FOR FREIGHT AND PASSENGER TRAINS

400 volts, 13 per cent, the average drop being 235 volts or 7.6 per cent.

A single 250,000-cir. mil electrically welded bond was used throughout. The cost of installation including oil and gasoline was 61 cents each. Pressed steel track ties were in use over most of the line and were replacing wood ties as the latter required it.

The trolley and feeder lines were sectionalized at Nogales, Maltrata, Alta Luz, and Boca del Monte.

At Orizaba the yards consisted of eight tracks located between the shops on one side and the station, store-houses, and round-house on the other side.

The ground at points was soft and the use of guy wires was quite objectionable generally and impracticable at many points. Towers were made up from 62-lb., discarded rails which were capable of supporting the wiring necessary for the 8 tracks. Special extensions were made which provided foundations at a reasonable cost which rendered guying at any point unnecessary; 44 of these towers were used in the Orizaba yard and 33 in the Cordoba yard, the latter costing \$102 each. Other lighter towers also made from old rails were used at bridges. The cost of these towers was \$75.48 each, Fig. 6.

There are seven tunnels on the first electrification, seven on the Cordoba, and two on the Paso del Macho extensions, a total of sixteen, all but two of which are on curves.

The total cost of the 29.5 mi. of distribution system including poles and fixtures was \$462,011 or \$15,661 per route-mile.

In 1926 the trolley line was extended from Orizaba to Cordoba, 16 mi. south, making a stub end feed from the Maltrata substation approximately 29 route-miles but feeder cut-offs at loops reduced the feeder length to about 25 mi.

This construction was similar to the original except that rail poles were used exclusively: Two 500,000-cir. mil copper feeders were used almost the entire distance. The total cost of this extension was \$233,556

or \$14,597 per route-mile. The estimated cost was \$231,500, but did not include the complete wiring of the Cordoba yard as was done.

In May 1928 the electrification was extended from Cordoba to Paso del Macho, 18 mi. farther south, making the total electrification 64 route-miles. A second substation was located at Potrero, approximately 39 miles from Maltrata and 8.5 mi. from Paso del Macho. The trolley construction on this last extension was the same as on the Cordoba extension except that only a single 500,000 cir. mil copper feeder was used between Cordoba and Potrero and no positive feeder at all from the substation to Paso del Macho.

Non-ferrous materials were used for hangers and span wires and copper weld messenger on the last extension, as this section is nearing the seacoast and it seemed advisable to use such material where steam locomotives are expected to operate at all frequently under the wires.

SUBSTATION EQUIPMENT

The original substation located at Maltrata contains two 3000-kw., 3000-volt d-c. three-unit synchronous-motor generator sets for supplying power to the original 29.5 mi. electrification. Fig. 8 shows a plan of the Maltrata substation, Fig. 9 the interior of the generator room, and Fig. 10 a schematic diagram of the wiring of the 3000-volt d-c. generators.

Power is purchased from the Puebla Tramway Light & Power Company at 42,000 volts, 60 cycles. Ample provision is made for housing all of the substation equipment, the transformers and high-tension switching occupying about one-half the building. The other half of the station is occupied by the motor generator sets and switching equipment; each motor generator set is protected by a high-speed circuit breaker and each of the outgoing feeders has also the same protection.

With the extension of the electric zone to Paso del Macho, making the total length of route approximately 64 mi., a second substation was installed at Potrero.

The power demands for this portion of the line, however, are much lighter on account of the easier grades, and this station contains two 1500-kw. units which are similar in other respects to the original equipment.

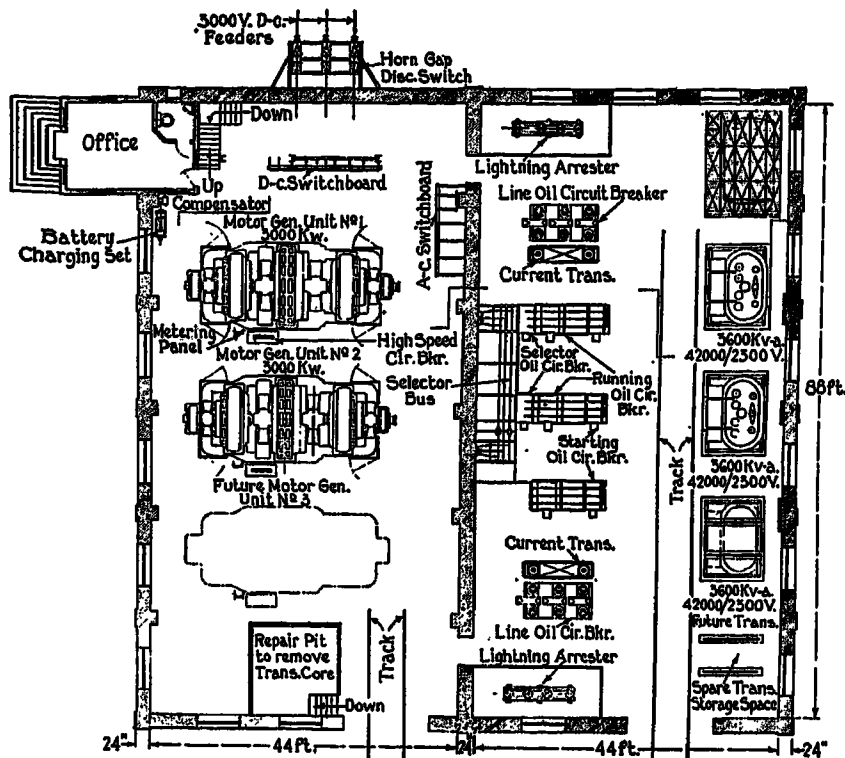


FIG. 8—PLAN OF MALTRATA SUBSTATION SHOWING LOCATION OF APPARATUS

This station is also supplied from the 42,000-volt, three-phase, 60-cycle circuit which forms a part of the power company's network.

Each substation building provides the necessary

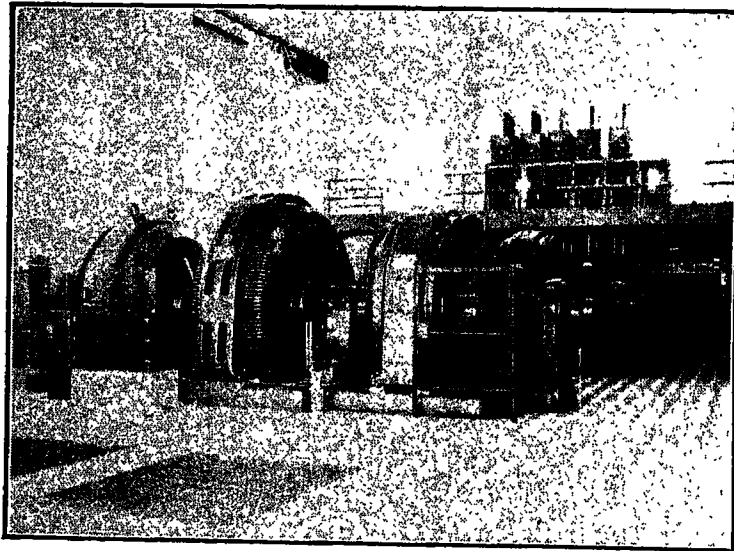


FIG. 9—INTERIOR OF MALTRATA SUBSTATION SHOWING TWO 3000-KW., 3000-VOLT MOTOR-GENERATOR SETS AND HIGH-SPEED CIRCUIT BREAKERS

space and foundations for a third unit when required. The equipment used is standard, being similar to that supplied the Chicago, Milwaukee & St. Paul, the Spanish Northern, and the Paulista Railways.

ELECTRIC LOCOMOTIVES

The initial motive power equipment for the Orizaba-Esperanza section included ten locomotive units suitable for handling both passenger and freight service. These locomotives are of the twin-geared six-motor

articulated-truck type capable of operating at a maximum speed of 40 mi. per hr. and provided with equipment for regenerative electric braking.

The cab is of the box type mounted on two equalizer frames which in turn are carried upon three two-axle trucks. The motors are twin-geared to each axle through cushion type gears.

The motors are designed for 1500 volts per commutator, two being connected permanently in series. An unusual feature of this locomotive is the provision for removing the motor wheels and axle from any of the trucks without lifting the cab. These units are so constructed that the wheels, axle, and motor can be

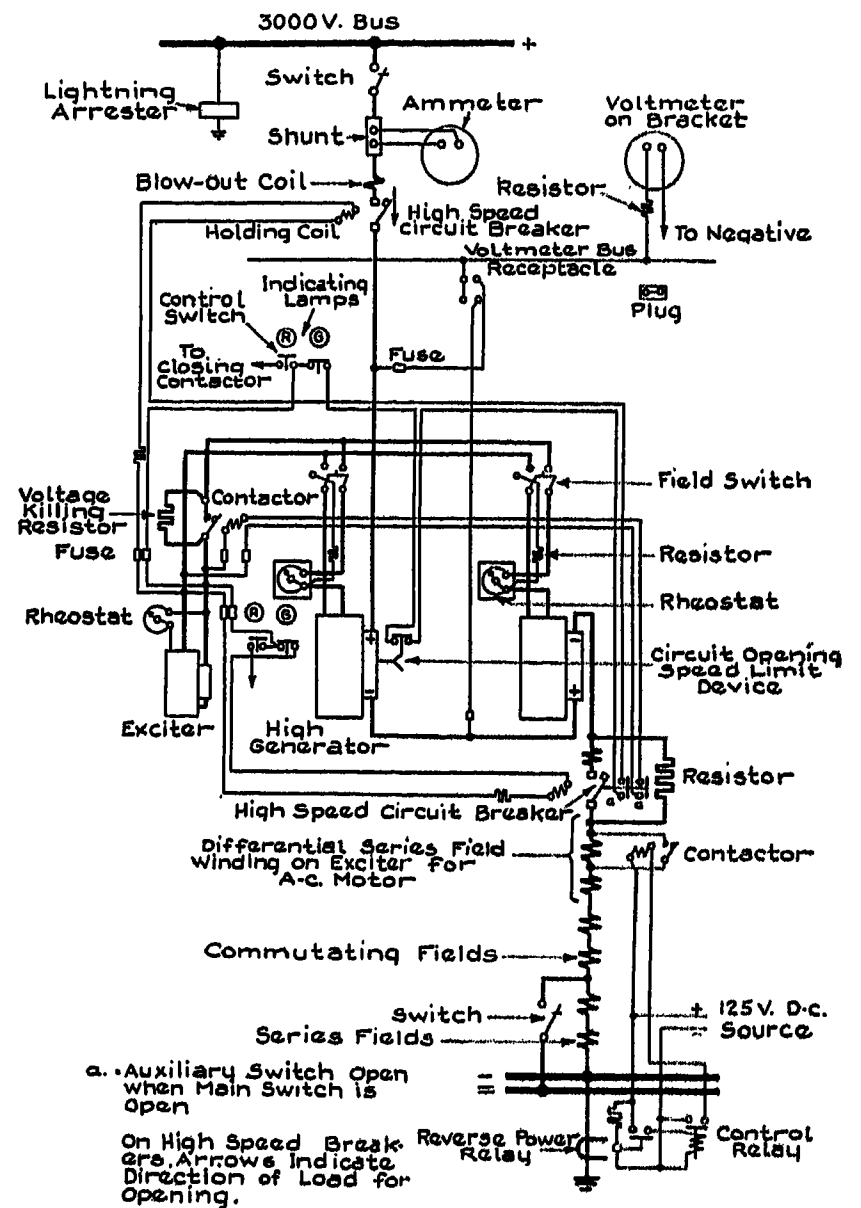


FIG. 10—SCHEMATIC DIAGRAM OF WIRING OF 3000-VOLT D-C GENERATORS

dropped into the pit after first disconnecting the motor leads or the wheels and axle may be taken out alone by propping up the motor and side frames.

The auxiliary machinery consists of a 3000/1510-volt dynamotor with a 65-volt control generator mounted on the shaft extension; a 1500-volt regenerative exciter set; two 1500/3000-volt motor-driven blowers and two 1500/3000-volt air compressors. The two blowers and the two compressors normally operate in series across the 3000-volt circuit with their mid-points connected to the mid-point of the dynamotor for equalization. The regenerative exciter set operates from the 1500-volt circuit of the dynamotor. The scheme of operation

provides a means for operating one compressor or one blower from the 1500-volt dynamotor bus in case of failure of the other unit. This arrangement also permits of operating the compressors and blowers in case of the failure of the dynamotor.

The locomotives are equipped with electropneumatic control for non-automatic multiple unit operation. A master controller in the engineman's cab at each end is arranged to give a total of 31 accelerating steps, distributed through the three groupings of the motors, a full-field and two reduced-field running steps with each of the three combinations. This gives a total of nine running points which, for a given tractive effort of 50,000 lb. and 2700-volt line, corresponds to a speed range of from approximately $5\frac{1}{2}$ to $26\frac{1}{2}$ mi. per hr. and correspondingly higher speeds with lighter loads.

The main motor circuits are protected by a high-speed circuit breaker which also serves as a line breaker as well as to give overload and short-circuit protection.

Current is collected from an overhead slider pantograph, one of which is located at each end of the cab roof. These collectors have a range of from 15 ft. 5 in. to 24 ft. above the top of the rail.

With the extension of the electrification from Orizaba to Paso del Macho additional motive power was required and for this purpose two locomotives, duplicates of the original design, have recently been delivered. Fig. 11 shows a locomotive attached to a regular passenger train at the Maltrata station.

Below are given the electrical and mechanical data on these locomotives:

TABLE IV

DATA ON ELECTRIC LOCOMOTIVES	
ELECTRICAL DATA	
Nominal voltage of system.....	3000-volt d-c.
Tractive eff., 1 hr. blown (3000-volt).....	54,000 lb.
Speed at 1 hr. rating, full field.....	19 m. p. h.
Total horsepower, 1 hr.....	2736
Tractive eff., con. 3000-volt full field.....	48,500
Speed at continuous rating, 3000-volt.....	19.5 m. p. h.
Total horsepower, continuous.....	2520
Number of motors.....	6
Type of motors.....	GE-278-A-1500/3000 volts
Gear ratio.....	90/18-5.00
Tractive eff. at 30 per cent tract. coef.....	92,700 lb.
MECHANICAL DATA	
Track gage.....	4 ft. 8 $\frac{1}{2}$ in.
Wheel arrangement.....	04440
Diameter of drivers.....	46 in.
Number of driving axles.....	6
Total wheel base.....	40 ft. 6 in.
Max. rigid wheel base.....	9 ft. 2 in.
Width overall.....	10 ft. 1 $\frac{1}{2}$ in.
Height over trolley locked down.....	15 ft. 2 in.
Length inside knuckles.....	52 ft. 11 in.
WEIGHTS	
Total weight on drivers.....	309,000 lb.
Dead weight per axle.....	12,150 lb.
Elec. and air brake equipment.....	135,000 lb.
Mechanical equipment.....	174,000 lb.

TRANSMISSION LINE

A 42,000-volt transmission line 17 mi. in length was constructed from the Tuxpango hydroelectric generat-

ing station of the Puebla Tramway Light & Power Co. to the Maltrata substation. Twin lines of 1/0 aluminum cable are supported on steel "A" frames with anchor towers at proper intervals.

A similar line of approximately the same length but with only a single set of conductors is now under construction from the same generating station to the new substation at Potrero. In the meantime the power company's line to Vera Cruz which the new line parallels is being used and switching arrangements are provided in the substation for reciprocal use of the lines when desirable.

ELECTRICAL OPERATION

The Orizaba-Esperanza section has now been in complete operation electrically since January 1925, thus making available the records for four full years of operating data and costs.

The great reduction in business resulting from the unsettled conditions caused by the disturbances of 1924 as well as new labor agreements and increased wages

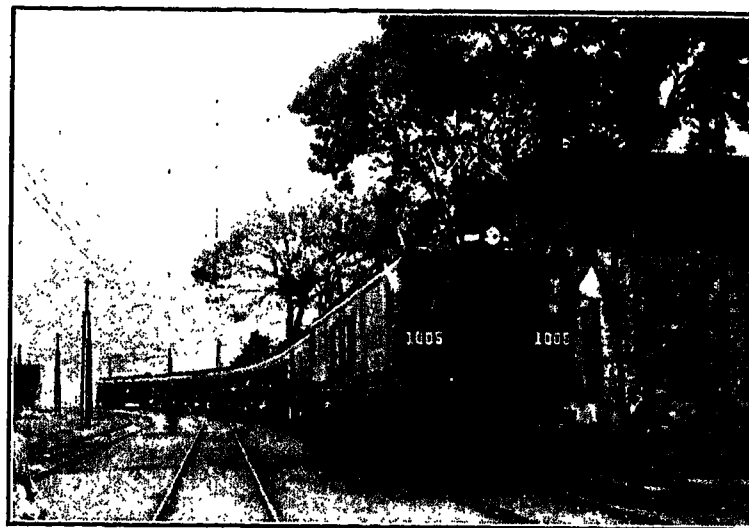


FIG. 11—PASSENGER TRAIN WITH 150-TON, 3000-VOLT LOCOMOTIVE AT MALTRATA STATION

had tended to make direct comparisons of operating costs look less favorable than they really were. A decrease in the tonnage to be hauled reduces operating costs to an extent but unfortunately not nearly in the same proportion and the capital charges remain practically the same. On the other hand increased wages and higher costs of fuel and materials usually tend to make electrification comparatively more profitable.

The operation has been very satisfactory and successful throughout. No serious difficulties have been encountered with any portion of the equipment. This may be measured fairly by reference to the complaint bill for the usual guarantee period which was less than \$3,000.

The general performance of the equipment may best be judged by the costs of maintenance, a fair average of which is given herein.

During the months of March and April 1928 the traffic over the Orizaba-Esperanza section reached a new maximum which was somewhat in excess of that

for steam operation which had been attained during the months of September and October 1921 which was used as a basis in the original study. This offered a favorable opportunity for comparing actual results of electrical operation with that for steam operation, as well as to check the estimates in the report leading to the electrification.

Detailed tabulations of the operating records for March and April 1928 with electrical operation were prepared for comparison with similar records as used in the report for September and October 1921 with steam operation.

A summary of this comparison follows:

TABLE V

	1921	1928	Difference	
	Steam oper. Sept. & Oct.	Elec. oper. Mar. & Apr.	Amount	Per cent of steam
Number of trains run.....	1,096	1,011	85	108
Number of cars handled....	9,238	12,840	3,602	139
Number of tons handled....	305,969	416,037	110,068	136
Number of train hours.....	4,577	2,718	1,859	60
Number of tons per train...	279	412	133	148
Number of cars per train...	8.43	12.70	4.27	150
Number of hours per train..	4.18	2.69	1.49	64
Cost enginemen's wages....	\$17,982	\$14,565	\$ 3,417	81
Cost trainmen's wages.....	14,222	10,721	3,501	76
Cost fuel oil or power.....	36,965	31,140	5,825	84
Cost locomotive repairs....	59,208	5,969	53,239	10
Enginehouse expense.....	3,391	1,945	1,446	58
Lubricants.....	2,776	92	2,684	3
Substation operation.....	..	2,154	2,154	..
Trolley maintenance.....	..	856	856	..
Total cost items affected...	\$134,544	\$67,442	\$67,102	50

Briefly stated, the 10 electric locomotives during March and April handled 36 per cent more tons than was handled by more than double the number of steam locomotives during September and October, with 8 per cent less trains and in 40 per cent less train hours on the road, and at 50 per cent of the corresponding total cost of steam operation for 26 per cent less tonnage handled; thus accomplishing a saving of \$67,102 for the two months, or at the rate of \$402,612 per year, which alone represents a return of more than 15 per cent on the gross cost of the electrification including electric locomotives. However, this amount does not represent actual saving since the cost of all classes of labor had considerably increased during 1922 and 1923 so that it is necessary to adjust the costs of the steam operation to have them indicate what they would have been if the increased traffic of March and April had been handled by steam and at the higher rate of wages, as was done by the electric locomotives.

Between October 1921 and the end of 1923 and before the electrification had been completed, new contracts were made with practically all labor involved in these operating costs, under the terms of which the rates of pay were materially increased. Enginemen's and trainmen's wages were increased on an average of

about 42 per cent, which higher rates were in effect in March and April 1928. The increases were:

	1921	1928	Per cent
Enginemen per round trip...	\$6.00	\$8.88	48.0
Firemen per round trip.....	2.88	4.44	54.1
Conductors per round trip...	5.50	7.20	30.9
Brakemen per round trip....	2.69	3.60	33.8

The wages of mechanics and others employed in the repair and care of locomotives were also proportionally increased but last year and the year previous thereto considerable reductions were made in this class of labor, to such an extent that no adjustment for wages in cost of repairs was considered necessary.

The average price paid for fuel oil during the months of September and October 1921 was \$1.09 per barrel but the price paid for same in March and April is given as \$1.29, an increase of 18 per cent.

In adjusting the cost of steam operation for September and October 1921 for the 36 per cent increase in traffic, it was considered inaccurate to assume that the cost would increase in the same proportion, since the number of trains required to handle the traffic is almost entirely determined by the northbound or up-hill traffic which exceeded the southbound by 32 per cent during March and April. It is also possible to take considerably heavier trains down than up the mountain grade.

The adjustment for increased traffic was consequently made on the basis of the increased number of steam trains that would have been required to handle the northbound business.

The passenger trains run north in March and April numbered 122 as against 89 in September and October, an increase of 33 trains.

The freight tonnage hauled north for the same period was 195,357 and 175,625, respectively, an increase of 19,732 tons. At an average of 330 tons per train which is the exact record for the steam locomotives, 60 additional freight trains would have been required to handle this excess freight tonnage, making a total increase of 93 trains or 14.95 per cent. On an already congested single-track line with infrequent passing tracks, a 14.95 per cent increase in the number of trains would ordinarily considerably lengthen the time per train, and consequently increase the cost of wages and fuel, but since the enginemen and trainmen are paid by the trip if made in ordinary time, and the run being unusually short, no allowance was made for this item. It was considered conservative to assume that all other costs of the items listed would be increased in approximately the same proportion as the number of trains operated, that is, 14.95 per cent.

When the costs of steam operation were adjusted on this basis as outlined, the direct comparison between steam and electric operation for traffic handled in March and April 1928 was:

	Steam	Electric	Reduction	
	Sept. & Oct.	March & April	Amount	Per cent
Enginemen.....	\$30,991	\$14,565	\$16,426	53
Trainmen.....	21,722	10,721	11,001	50
Fuel or power.....	50,139	31,140	18,999	38
Repair locomotives.....	68,059	5,969	62,090	91
Enginehouse expense.....	3,898	1,945	1,953	50
Lubricants.....	3,191	92	3,099	97
Substa. oper. maint.....	..	2,154	..	..
Trolley oper. maint.....	..	856	..	..
Total.....	\$178,000	\$67,442	\$110,558	62

In order to directly compare the above with the estimate in the original study on this subject the costs were placed on a yearly basis as follows:

	Steam	Electric	Saving	
			Indicated	Estimated
Enginemen.....	\$185,946	\$87,390	\$98,556	\$76,538
Trainmen.....	130,332	64,326	66,006	62,099
Fuel or power.....	300,834	186,840	113,994	71,790
Repairs to locomotives...	408,354	35,814	372,540	304,137
Enginehouse exp.....	23,388	11,670	11,718	15,105
Lubricants.....	19,146	552	18,594	13,735
Substa. oper. maint.....	..	12,924	..	..
Trolley oper. maint.....	..	5,136	..	..
Total.....	\$1,068,000	\$404,652	\$663,348	\$523,029

The above indicated yearly saving of \$663,348 in favor of electrical operation is 27 per cent greater than the estimate, but this was readily accounted for by the 36 per cent greater tonnage handled since any material increase in traffic should increase the savings also, and in a greater proportion.

This annual saving represents approximately 26 per cent earning on the gross cost of the electrification of the Orizaba-Esperanza district, which alone should be a very satisfactory result but other more indirect savings which cannot be so accurately segregated, such as wear on wheels and brake shoes, reduction of accidents from broken wheels due to over-heating while braking would, if fully valued, add many hundreds of dollars to the credit of electrical operation.

Perhaps the most valuable unlisted asset in the electrification is the increased capacity of the lines electrified. On March 18, 5381 tons of freight and two passenger trains weighing 741 tons, making a total of 6122 tons, were hauled from Orizaba to Esperanza which was a record for the district. The record day with steam operation was October 25, 1921, when 4008 tons of freight and two passenger trains weighing 640 tons making a total of 4648 tons were handled; 1474 tons or 31 per cent in favor of the electric operation, 14 trains being used in each case.

The total tonnage handled electrically on March 18, north and south, was 9659 and that for October 25, 1921 by steam was 6532. The excess for electric operation was 50 per cent. The train hours electric were 64.6; steam 83.4, a reduction of 18.8 train hours or 22 per cent with an increased tonnage handled of 50 per cent.

By increasing the train weight to 900 tons (metric),

for which the line and equipment are capable, it would be practicable to handle over the present line double the tonnage handled on March 18 with no additional facilities except for locomotives, cars, and power.

The ten locomotives now in service were expected to be sufficient to handle a maximum of 4200 tons or regularly 3600 tons in addition to two passenger trains per day in each direction between Orizaba and Esperanza.

This maximum was exceeded by 1181 tons or 28 per cent on March 18 and the average tons per day north bound for the month was 3350 tons but all ten locomotives were used on the maximum day.

The earnings on investment as shown are for the gross investment including the cost of electric locomotives. Had new steam locomotives been purchased these would have been charged as renewals or betterments and since sufficient new steam locomotives to handle an equal tonnage on a mountain district would cost approximately as much as the electric locomotives, it should be quite proper to deduct the cost of the locomotives from the cost of the electrification.

In the case of the Mexican Railway the cost of the electric locomotives was approximately 46 per cent of the gross cost of electrification and usually for heavy grade work this item will average between 40 and 50 per cent.

If the cost of the electric locomotives be deducted from the total cost of electrification the savings from electric operation as shown would be equivalent to an earning of 47 per cent on the net cost.

The entire 64 mi. has been in full operation for about a year, but the records are not yet available for a comparison such as is given for the original electrification and it will not be possible to have them so accurate as long as the 48 mi. on the Vera Cruz end is operated by steam.

The total cost of the 64 route-miles of electrification including electric locomotives was approximately \$3,606,937. The original study gave an estimate of \$4,032,500.

The experience gained from two years' operation in the Orizaba-Esperanza district made it evident that the traffic could be handled with a less number of locomotives than had been considered necessary, so that this item was reduced by approximately 20 per cent.

Discussion

D. C. Jackson: Mr. Cox's paper is a notable one because it shows carefully gathered statistics of comparative cost of steam operation with electric operation over the same route with appropriate coefficients to transform somewhat heavier traffic of the electric period back to the steam period, or vice versa. The only fault with that lies in the fact that the time has been so short that the comparison is on a monthly basis rather than a complete annual basis, although transferred to the annual basis, and it is to be hoped that Mr. Cox may ultimately bring forward a paper that gives an entire actual twelve months of experience. If it is as favorable as his present paper would indicate, it cer-

tainly will be reassuring to the railroad executives and operating people.

One of the difficulties that has existed with respect to electrification of railroads of heavy type, has lain in the fact that the electrical people, and particularly the manufacturers and power companies, have failed to recognize that the railroads have a transportation problem, not a problem of using electrical machinery, and primarily it is one of the great problems of the United States; in fact, it is one of the great problems of the world.

Another difficulty has rested in the fact that data of comparing operating results, including costs, have not been clearly analyzed and made generally serviceable to railroad executives and the railroad-using public. Mr. Cox is starting on a path which is worthy of extension.

Sidney Withington: In connection with Mr. Cox's paper, in presenting the savings accomplished by the railroad electrification, it seems to me it would be more convincing and more valuable if he had also discussed more in detail the effect of modern steam motive power. It is the duty of railroad electrical engineers to do business with hard-headed steam railroad executives and they want to know not only the savings due to electrification in comparison with pre-war equipment, so to speak, but they want to know what the savings of electrification are in comparison with modern steam motive power, equipped with feed-water heaters, super-heaters, and all the other elements which have been developed to increase the efficiency of operation and the capacity of steam locomotives. I think any comparison of the costs of electrification as compared with steam operation should include that basis. Mr. Cox's reference to modern steam locomotives tells only half the story.

Mr. Cox refers to the fact that non-ferrous material is used. I think this is of importance in showing the trend of electrification power-distribution design. The engineers who are responsible for the design of distribution systems are more and more clearly realizing the necessity of installing material that will stay in service, and reducing as far as possible the maintenance problems which of necessity interfere with operation and are interfered with by operation. This is of course of special importance where steam locomotives are operated in the electric zone.

W. B. Potter: Electrification of the Mexican railways as described by Mr. Cox is an excellent example of what may be done to improve the service and at the same time accomplish such reduction in the cost of operation as to show a substantial return on the investment for the new type of motive power. I would call particular attention to the important part which the electric locomotives had in obtaining this economic showing, both as to operation and fixed charges. The cost of maintenance as compared with steam is an appreciable reduction in the operating expense. The relative cost of electric power and fuel for steam locomotive will vary in nearly every case, but the relative maintenance in favor of electric locomotives may always be expected to show an appreciable gain. As affecting the fixed charges, the cost of the electric locomotives is a large item in the total cost of electrification, amounting to 46 per cent in the case of the Mexican Railways and 42 per cent in the Chicago, Milwaukee & St. Paul. The cost of the locomotive has, therefore, an important bearing on the amount to be charged to depreciation, particularly as the locomotive depreciation is at a higher rate than other features of electrification. The cost, maintenance, and depreciation of the substations and overhead construction are relatively of small importance as compared to the locomotives.

J. B. Cox: In reference to Mr. Jackson's criticism it should be explained that the records for several months were gone over carefully, and in the case of steam the two months were selected by the management as being most nearly representative of what they expected in the future and wished to prepare for immediately.

On account of previous conditions of operation only four months of steam operating records were at all suitable for the study, these being July, August, September, and October, 1921. After a general survey of the past records and a careful study of these four months, September and October were selected for the more detailed analysis.

In the case of electrical operation, the months of March and April were designated for the comparison by the chairman of the Board of the Railway, because the traffic over the road during these two months was the heaviest in its history for a like period and was thought to be most desirable for the comparison.

In this instance also the records for January, February, March, and April, 1928, were carefully studied and compared with practically the entire period of electrical operation, precisely as had been done for September and October with steam operation.

Table VI, which is published herewith, gives the operating costs involved for the four months steam operation mentioned, the four corresponding months electrical operation, and the records for 39 months of electrical operation which cover practically the entire period since the original electrification was in complete operation.

The 1928 record includes eight months operating cost of the newly completed divisions between Orizaba and Paso del Macho, or for the entire 64-mile section, and are therefore not directly comparable with the records for 1925, 1926, and 1927. A comparison of the four months steam operation with the corresponding four months electrical operation indicates a total saving of \$141,964 for the four months period, or 51 per cent in favor of electrical operation, which is at the rate of \$125,892 per year, whereas the two months comparison used in the paper showed a saving of only \$102,612 or 50 per cent, before any adjustments were made for increased tonnage and wages in either case. Unfortunately the records of the ton-miles for July and August, 1921, were not recorded in the report, but judging from the locomotive miles and operating costs the increase in ton-miles during the four months electrical operation would be about 30 per cent as against 26 per cent, for the two months period, thus indicating that the two periods would show about the same rate of earnings on the investment.

These records, which in each case have been supplied by the operators and approved by them, should encourage alike the electrical industry and the railroad operating fraternity for a mutual interest in the electrification of railroads.

Practically all the figures presented are taken from official records, used originally in reports made at the request of the management of the railroad company, and are perhaps more accurate and free from adjustments than any others published to date. Space was not available in the paper for these details and therefore explanations have been abbreviated as much as possible. The records may be had in considerably more detail, and undoubtedly will soon be published.

Referring to Mr. Withington's remarks, it may be of interest to state that 30 per cent of the locomotive-miles in September and October were made by the ten new Consolidation locomotives referred to in the paper. No advantages were claimed because of this fact in favor of electrification, for the item of repairs to locomotives which would have been most affected, for the reason that the shop was behind with this work at the time and had continued at the same rate, through the period considered.

It was supposed that the best steam locomotives then available had been supplied. At that time, 1921, the steam locomotive had not nearly reached its present state of efficiency. The records of these new steam locomotives in this instance did not indicate that the growing traffic could be handled by them economically over the single-track line. Double tracking would have been too expensive for serious consideration, about double the entire cost of electrification.

TABLE VI
MEXICAN RAILWAY COMPANY
OPERATING COSTS ORIZABA—ESPERANZA DISTRICT

For 4-Month Steam Operation 1921						
	July	August	Sept.	Oct.	Total	Yearly rate
Enginemen.....	\$7,548	\$9,625	\$8,476	\$9,507	\$35,156	\$105,468
Trainmen.....	5,745	6,720	6,707	7,508	26,690	80,040
Fuel.....	19,369	21,570	17,551	19,413	77,903	233,700
Repairs.....	24,887	27,523	28,832	30,426	111,668	335,004
Enginehouse.....	2,028	1,427	2,185	1,305	6,945	20,835
Lubricants.....	1,095	1,287	1,412	1,364	5,158	15,474
Total.....	\$60,672	\$68,152	\$65,163	\$69,523	\$263,510	\$790,530
1000 ton miles.....			4,899	5,052		
Locomotive miles.....	58,844	61,513	57,541	61,822	239,721	719,163
For 4-Month Electrical Operation 1928						
	Jan.	Feb.	March	April	Total	Yearly rate
Enginemen.....	\$4,776	\$5,517	\$7,839	\$6,726	\$24,858	\$74,574
Trainmen.....	2,850	3,619	6,010	4,711	17,190	51,570
Power.....	13,740	14,054	14,560	16,580	58,934	176,802
Repairs.....	2,888	2,534	2,251	3,717	11,390	34,170
Enginehouse.....	777	756	965	980	3,478	10,434
Lubricants.....	22	51	47	45	165	495
Substation.....	869	944	1,052	1,102	3,967	11,901
Distribution.....	439	269	444	412	1,564	4,686
Total.....	\$26,361	\$27,744	\$33,168	\$34,273	\$121,546	\$364,632
1000 ton miles.....	5,062	5,953	8,445	7,420	26,880	80,640
Engine miles.....	20,780	23,490	32,119	29,256	105,645	316,935
For 39-Month Electrical Operation 1925-1928						
	1925 Oct., Nov., Dec.	1926 Year	1927 Year	1928 Year	Total 39 months	Average yearly rate
Enginemen.....	\$9,221	\$43,012	\$54,992	\$80,835	\$188,060	\$57,865
Trainmen.....	4,789	25,970	34,193	53,033	117,985	36,303
Power.....	40,531	163,668	164,840	195,680	564,719	173,760
Repairs.....	4,493	21,768	36,868	42,514	105,643	32,505
Enginehouse.....	5,644	11,562	9,998	16,810	44,014	13,543
Lubricants.....	747	2,173	668	733	4,321	1,320
Substations.....	4,966	15,130	12,831	13,309	51,236	15,765
Distribution.....	2,587	9,308	4,510	5,775	22,180	6,825
Total.....	\$72,978	\$292,591	\$318,900	\$413,689	\$1,098,158	\$337,895
1000 ton miles.....	9,714	43,856	57,625	99,028	210,221	64,683
Engine miles.....	37,898	199,424	231,895	355,093	824,310	253,633

In general, where electrification has been compared with the most modern steam power, the initial cost of steam or electric locomotives for equal service has come out about the same. The operating savings effected by electrification were 50 per cent over old steam locomotives, but only about 30 to 35 per cent over modern steam locomotives. Where the cost of the locomotives is about the same in each case, and is about 50 per cent of the gross cost of electrification, the visible return on the capital investment for modern steam power would be at approximately the same rate as that for double the investment required for electrification, but the benefits received from electrification, in the way of improved service and increased capacity, are much greater, and usually will justify the additional expenditure. Much depends on the extent to which it is desired to improve the service and the increase in the line capacity required and the rate at which traffic is increasing.

If all these items are above normal, electrification will usually show an advantage sufficient to make the additional cost fully justified, even when compared with the most modern steam power. Where double tracking and new steam locomotives are necessary, it will be found that electrification will promise a much higher rate of return on the required investment, and in most instances will cost considerably less.

No doubt many such economic mistakes have been made in double tracking in the past, due largely to the fact that the electrical engineer has not been sufficiently experienced in railway operation to be able to present the case convincingly to the railway operating official, whose experience with electric traction has been equally limited.

The power companies have also failed to take advantage of an opportunity to increase their income through a misapprehension as to the effect a railway load might have on their system.

Contact Wire Wear on Electric Railroads¹

BY I. T. LANDHY²

Non-member

Synopsis.—It is the purpose of this paper to present such data on the subject of contact wire wear as the electric operation of four railroads has made available. Design of overhead system and pantographs, lubrication of pantograph shoes, presence of steam locomotives under catenary, ice on contact wire, condition of roadbed, speed of trains, and amount of current collected at pantograph shoe

all have a bearing on the rate of wear, the relative importance of each of these factors being a moot question. The four railroads contributing are the New York, New Haven and Hartford, the Chicago, Milwaukee, St. Paul and Pacific, the Pennsylvania, and the Illinois Central.

* * * * *

GENERAL DESCRIPTION

THE New Haven's initial electrification in 1907, of approximately 21 route mi. of four tracks from Woodlawn, N. Y. to Stamford, Conn. was extended in 1914 from Stamford to New Haven, Conn., with about 39 route mi. of four tracks.

High-speed suburban and through passenger, and heavy freight traffic in the electrified zone are supplied with 11,000-volt, 25-cycle, single-phase, a-c. power. Speeds up to 70 mi. per hour are attained, the maximum weight of a train being 3800 tons. In addition, there is still a number of steam trains operated, these being mostly heavy-tonnage freight trains. A considerable steam traffic was operated in the electrified zone initially, but since, has been supplanted almost entirely by electric except for that mentioned above.

The contact wire, which is 4-0 grooved of 40 per cent conductivity bronze, normally varies from 16 to 22 ft. above top of rail, the gradient at points of change averaging about 1 per cent. It is supported from an auxiliary 4-0 grooved copper wire at 10-ft. intervals by malleable iron or bronze clips. The contact wire tension varies between 100 lb. and 3800 lb. depending upon the temperature.

The pantograph shoes are of pressed steel, those for the larger locomotives of No. 11 U. S. gage, and for the multiple-unit equipment and smaller locomotives, of No. 14 B. W. G. Normal pantograph pressure on the wire is about 18 lb., increasing to about 25 lb. when the pantograph is traveling down, and decreasing to about 10 lb. when traveling up. Although lubrication was attempted for a time, the shoes are normally not lubricated. The normal maximum current collected is about 200 amperes per pantograph shoe.

Each unit of motive power used in road service carries two pantographs, although normally but one is used at a time. A considerable number of both passenger and freight trains is double headed, which involves

two pantograph passes for each movement of such trains. Multiple-unit trains are normally made up with a ratio of one motor car to each two trailers. An average of 25,000 pantograph passes per year per track has been assumed.

The Milwaukee began electrical operation in 1915 of 441 route mi. of line, between Harlowton, Mont. and Avery, Idaho, and in 1919 of an additional 218 route mi. between Othello and Seattle-Tacoma in Washington.

The services operated electrically are through passenger and freight. D-c. power at 3000 volts is supplied the locomotives, about ten per cent of that supplied being returned through regenerative braking.

A ½-in. Siemens-Martin steel messenger supports two parallel 4-0 grooved copper contact wires by means of loop hangers alternately clipped to one and then the other. The height of contact wire above top of rail varies from 17 ft. to 24 ft. 2 in.

Each pantograph consists of two independent steel shoes with hard-rolled copper contact strips. The strips on each shoe are separated to provide a trough between them for the lubricant. The pantograph pressure on the contact wire is 30 lb., making the pressure per shoe equal to 15 lb.

The Pennsylvania's suburban service between Philadelphia and Paoli, Pa., about 20 route mi., was electrified in 1915, and between Philadelphia and Chestnut Hill, about 12 route mi., in 1918.

The inclined catenary type of construction in use between Philadelphia and Paoli consists of a ½-in. steel messenger supporting a 1-0 round copper auxiliary messenger at 30-ft. intervals, the 3-0 grooved phono-electric contact wire being suspended from the auxiliary messenger by clips spaced at 15-ft. intervals, staggered with respect to the hangers. The construction in use between Philadelphia and Chestnut Hill is similar to the above except that the auxiliary messenger is a 2-0 grooved copper wire. Normal contact wire height is 22 ft. above top of rail, the gradients down to lower heights varying between 0.12 and 1.2 per cent.

These electrified tracks are used principally by multiple-unit suburban trains, a relatively small

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3. Approximately 40 mi. of the steel messenger has been replaced by ⅝-in. high-tension bronze cable, due to the corrosion of the former by locomotive gases.

electric locomotive mileage being made for experimental purposes, also. Steam locomotives are used in the electrified territory, too. A-c. power is supplied at 11,000 volts, the multiple-unit cars drawing normally a current of 20 amperes with a maximum of 80 amperes during acceleration. The schedule speed of these trains is high and the station stops are relatively close together so that maximum speeds well up toward 60 mi. per hr. must be attained.

The pantograph, the shoes of which are of mild steel, have been designed for as low an inertia as possible. Normal pressure against the contact wire is 18 lb.

The Illinois Central, in 1926, electrified its suburban service between its Chicago terminal and Matteson, Ill., Blue Island, Ill., and South Chicago, a total of approximately 39 route mi.

The catenary, except for yards, sidings, and cross-overs, consists of a 0.81-in. composite copper-copperweld messenger cable supporting, at 15-ft. intervals, a $\frac{3}{8}$ -in. auxiliary messenger cable which in turn supports two 4-0 grooved copper contact wires. These are in the same horizontal plane, each wire being clipped to the auxiliary messenger at 15-ft. intervals, the clips being staggered with respect to the hangers and clipped to first one and then the other contact wire. In the denser traffic zone, north of the junction with the South Chicago branch at 67th Street, two 3-0, 80 per cent conductivity, grooved cadmium-bronze contact wires are used, each wire suspended at 20-ft. intervals from a $\frac{1}{2}$ -in. auxiliary messenger cable, the main messenger being the same. The yard catenary is composed of a 4-0 grooved copper contact wire suspended by rigid hangers from a $\frac{3}{8}$ -in. phono-electric bronze messenger. Normal contact wire height is 22 ft. with an allowable gradient of 1 per cent down to lower heights to clear overhead obstructions, minimum height being 16 $\frac{1}{2}$ ft.

D-c. power at 1500 volts is supplied the multiple-unit suburban trains which consist of from two to eight cars. Speeds up to 65 mi. per hr. are attained in order to maintain a fast schedule with fairly frequent stops. The accelerating current averages 770 amperes per pantograph, the normal running current being 200 amperes. There is only a small amount of steam operated traffic, (mostly switching), directly under the wires, but the through passenger and freight tracks are adjacent to the suburban tracks so that locomotive gases are more or less always present.

The pantographs have, in general, galvanized sheet steel bodies faced on the contact surface with hard-rolled copper strips, but a few bodies are of aluminum. The life of contact strips is approximately 10,000 mi. Normal pantograph pressure is 22 lb. All pantographs are lubricated, a trough between the contact strips holding the grease.

The multiple-unit cars operate in pairs, one being a motor car carrying two pantographs, only one of which is normally in use, and the other a trailer.

DISCUSSION

The design of the catenary system is important, aside from its functions of supplying a contact plane for the current collector and a distribution system for the power, in determining the rate of wear of the contact wire or wires. It will be noted that in each of the four systems described special precaution has been taken to obtain flexibility in the contact plane. The line must be flexible enough to insure intimate contact between wire and pantograph and yet not so flexible as to permit the formation of a large wave ahead of the pantograph as it moves forward. The requisite flexibility can best be obtained by staggering the points of support of the contact wire with respect to the messenger, while at the same time damping out the unwanted harmonic wave ahead of the pantograph by means of as high a tension in the contact wire as it will permit. It will be readily seen that a wave propagated ahead of the pantograph has no serious effects as long as its rate of propagation, the speed of the pantograph, and the mass of the contact plane remain of the same relative magnitude; but let any one of these factors change and the smooth passage of the pantograph under the contact wire is interrupted to the mutual detriment of both. Thus, it is always at those pull-offs where the free vertical movement of the wire is restricted and at such points as have a more-than-normal concentration of weight that accelerated contact wire wear is found. A large proportion of any contact-wire system wears slowly and uniformly, yet it is the small proportion of places where the wear is accelerated that require replacement soonest. At gradients in the contact system the inertia of the pantograph causes a greater or lesser pressure on the wire, greater if moving down and lesser if moving up. At a certain pressure, which obviously should be the normal pressure, the wear will be a minimum, any greater or lesser pressure resulting in increased wear; if greater, due to increased friction, and if lesser, due to increased burning caused by insufficient contact.

Pantograph design resolves itself into a judicious composition of the following essentials: (1) sufficient current collecting surface; (2) light weight moving parts; (3) sufficient uniform upward pressure; and (4) freedom from friction in the bearings. The effect of the first will be taken up further on. The necessity of having all moving parts as light in weight as possible is apparent. All changes in grade of the contact wire require that the pantograph follow them, and, in order to minimize the wear, especially at the *change* in grade, the inertia of the pantograph must be small. A sufficient uniform upward pressure must be present to permit of current collection without arcing. Friction in the pantograph bearings may be classed as additional inertia since its effect is the same.

It is probable that if the contact surface of the pantograph were of some metal dissimilar to that in the contact wire a lower rate of wear of the latter would result, on the theory that the coefficient of friction

between dissimilar metals is lower than that between similar metals.

The question of lubricating the pantographs produces a diversity of opinion. The New Haven and Pennsylvania do not lubricate, while the Milwaukee and Illinois Central do. The effect of lubrication *per se* will be taken up at length further on. Just now it may be well to point out that the decision to lubricate or not is probably influenced by the presence under the wire of steam locomotives. The experience of the Milwaukee shows that locomotive smoke and the sand blown from the stack of oil-burning locomotives in sanding the fire-tubes adheres to the grease film on the wire forming an actively abrasive surface. No doubt some similar action would be present in localities where dust or sand storms are prevalent. On lines such as the New Haven's and Pennsylvania's, where a considerable steam traffic passes directly beneath the contact wire, the presence of grease on the wire might increase the wear.

Intrinsically, lubrication plays an important role in reducing wear. Extended measurements and observations on the Milwaukee show that, on long tangents where the contact wire is in the middle of the pantograph the greater part of the time, the lubricant becomes depleted and wear is increased. On the other hand, on curves where the pantograph is wiped across the contact wire due to the chord type of catenary employed, the wear is less, the lubricant from the ends of the pantographs being distributed over the whole surface. A comparison of contact wire measurements shows that there is approximately 30 per cent more wear on tangent track than on curves.

Further evidence of the effect of lubrication is found in tunnels. Here, where the wires are sheltered from sun, rain, dust, and frost, the wear is approximately one-half that on exposed tangent track. Other factors may contribute to this end, but that the shelter of the tunnel is the dominant one is shown by the fact that where water drips from the tunnel roof the wear is greater. The limited experience of the Illinois Central corroborates these observations.

The presence of steam locomotives under the wires, aside from the abrasive deposits left by them, produces a certain corrosion, small though it may be, of the contact surface. Any pitting from this cause removes a small amount of the wire and leaves a roughened surface which is abrasive to a degree. The total effect is probably insignificant.

Ice on the wires separates them from the pantograph, causing small arcs to be drawn. The pits formed by these arcs are substantially the same as those mentioned in the preceding paragraph except that they are larger and hence more injurious. Accelerated wear is in progress at the pitted spots until they are worn smooth again. The kind of service operated is largely influential in determining the total effect of ice deposits on contact wire wear. With frequent suburban service providing less time for the deposits to form the effect is

probably of small moment, especially as on the Illinois Central, when there is danger of the formation of sleet all pantographs are raised. With a relatively small number of pantograph passes a day as on the Milwaukee, particularly when the territory served is subject to more or less frequent sleet storms, the wear occasioned by such deposits is important. It may be said, then, that the burning, and therefore the wear, due to ice on the wire is less per pantograph pass where the frequency of the passes tends to keep the surface of the wire clear.

The condition of the roadbed affects the riding qualities of the cars, which in turn affect the pantographs carried by them. A sudden drop due to a low rail joint or frog point may cause the pantograph to leave the wire momentarily, drawing an arc, and producing

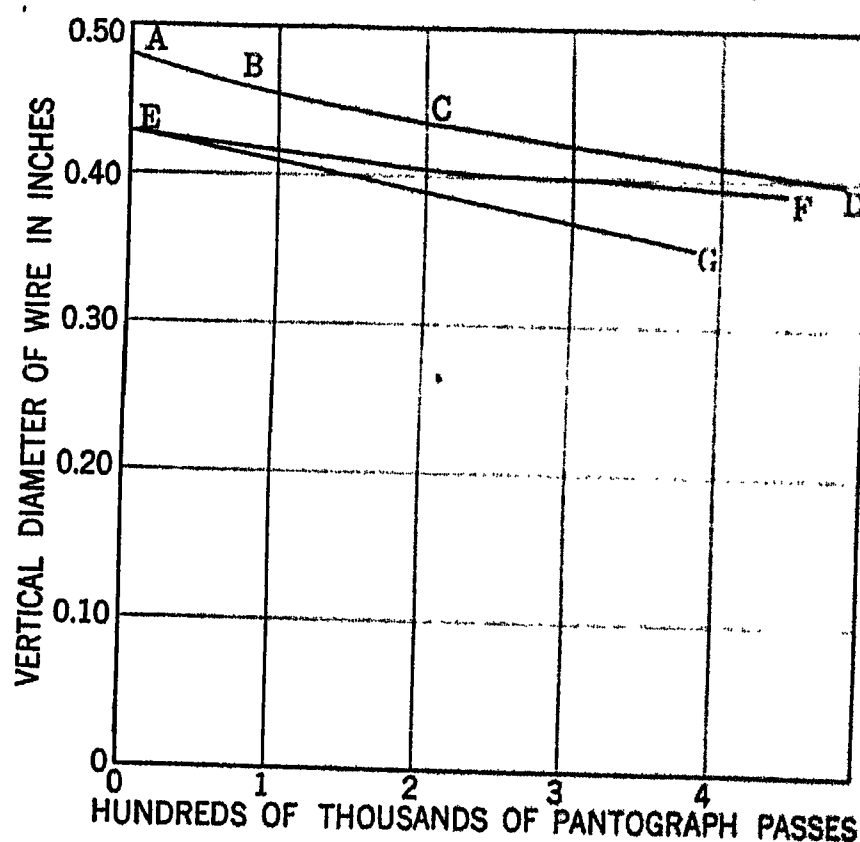


FIG. 1

A-B = 4-0 on C. M. St. P. & P. R. R.
 A-C = 4-0 on I. C. R. R.
 A-D = 4-0 on N. Y. N. H. & H. R. R.
 E-F = 3-0 on I. C. R. R.
 E-G = 3-0 on Pennsylvania R. R.

excess wear at the point where the pantograph resumes contact with the wire. The net effect may be said to be the sum of the effects of a change in gradient of the contact wire and the arcing caused by sleet. The wear due to this cause will probably be noticed most in the winter time when the roadbed is frozen and is difficult to resurface, particularly as at this season the pantographs are required to handle an additional electrical load due to the heater current being drawn.

The experience of the New Haven has been that generally the higher the speed of the train, the less the wear of the contact wire. This is borne out by the experience of the Illinois Central in a territory where four tracks carry high-speed express and special trains and two tracks relatively low-speed local trains.

The effect on contact wire wear of the amount of current collected is not so well known. The general impression is that as far as the effect of current alone

is concerned, the greater the amount of current, the greater the wear. Actually, it is difficult to determine the facts from experience because of the obscuring effects of other factors.

In the curves shown in Fig. 1 are given the relations between the vertical diameter of the contact wire and the number of pantograph passes. The curve for the New Haven takes into account all measurements made; that for the Milwaukee those measurements which represent maximum wear on the main line; that for the Pennsylvania only those measurements at places most susceptible to wear; and those for the Illinois Central all measurements.

In conclusion, then, for the purpose of minimizing contact wire wear it is necessary that the contact wire system be flexible, have little or no concentrated weight, and have gradual transitions from one height to another; that the pantographs be light, free moving, and actuated by sufficient pressure to insure good contact with the wire; that the question of lubricating pantographs be decided after considering such other factors as the presence or absence near the wire of abrasives which might adhere to the lubricating film; and that the condition of the roadbed be taken into consideration. Ice on the wires is abrasive and difficult to combat successfully. The speeds of trains and amounts of current collected are variables at best and probably do not affect the rate of wear appreciably.

Discussion

D. C. Jackson: A statistical paper like this one is very desirable because it does have definite influence upon estimates of operating expense from the maintenance aspects.

Sidney Withington: In connection with Mr. Landhy's paper, lubrication of the trolley wire or pantograph shoe is I think one of the fundamental problems in railway electrification which must be solved in the not distant future. It is a question as to whether the trolley wire be lubricated or the pantograph shoe. It is not satisfactory to swab a lot of lubricant on the pantograph shoe when the locomotive or car is at a terminal, and trust that that will stay on the pantograph and properly distribute itself along the trolley wire. This method is likely to lubricate everything including the clothes of the passengers, the road ballast and the car roofs in the vicinity of the terminal, and very little trolley wire after the first few thousand feet. Some better method must be developed.

One very interesting difference in practice in this country as compared with practice abroad, is in the pressure of the pantograph against the wire. We operate in this country with pantograph pressures of 15, 18, and over 20 lb., whereas abroad a pressure of 7 or 8 lb. is common, with the current collections often about the same magnitude as ours. That is largely due to the design of European pantographs in which is employed an auxiliary bow which follows the slight unevennesses in the contact wire and prevents arcing where there is a sudden change of elevation or a hard spot. Some day I think we will come to some such scheme as that, a moving part on the top of the pantograph which will enable us very considerably to reduce the pressure on the trolley wire.

The material of the pantograph must also be studied much more carefully than it has been thus far. It is possible that chromium plating may have some value in this connection.

In connection with the effect upon the trolley wire of the

amount of current which is collected, we are operating a branch line between Providence and Fall River, at 600 volts nominal pressure. The operation there is with the sliding shoe and the current densities are relatively quite high. We have noticed that where the trains leave stations (where the acceleration is taking place and the current is relatively high), the wear on the trolley wire is considerably greater than the wear on the same trolley wire as the trains approach the station where the current is zero, or very slight, but where the speed is about the same as where the trains are leaving the station. This seems to indicate that current density has something to do with the wear.

C. S. Anderson: There is one point which I wish to develop. This is in connection with the effect of the *composition* of the contact wire on its own rate of wear. Some years ago, we departed in many instances from the use of copper contact wires and used bronze contact wires to gain strength and also resistance to wear. However, one must distinguish between the bronzes and choose which type is best. The *tin-copper* alloys, often called phosphor bronze, or silicon bronze, depending on the deoxidizing agent employed, were the first type of bronzes to be used in contact wires. However, in the last year or two, the *cadmium-copper* alloys have been selected for several important lines, and it is of value to note that the results obtained with the cadmium bronzes are better than those obtained with the older tin bronzes.

In grades having equal strength, the conductivity of the cadmium bronzes is much higher and they resist *mechanical* wear as well as the tin bronzes, and they resist *electrical* wear much better. So on operating railroads where these types of wear are always found combined, it is not surprising to see the evidence piling up to show that the cadmium bronzes make more durable contact wires. This situation is evident in the graph on the third page of Mr. Landhy's paper. Curve *E-F* is for cadmium bronze. Note that its slope is decidedly less than the slopes of the other curves which are for copper or for tin bronzes.

In other words, the rate of wear under operating conditions is less for the cadmium bronze than for the tin bronze. This conclusion is confirmed by plotting on the same graph the results of field tests extending over thirty-two months, just completed by the Chicago Rapid Transit Company. Their tests were on cadmium bronzes. Plotting the results of their test we obtain a curve that lies parallel to Curve *E-F* in Mr. Landhy's graph, showing that the slower rate of wear of cadmium bronze is again confirmed.

Finally, it is of value to note that the cadmium bronzes will not become hot-short or brittle if overheated as by a short circuit. This embrittlement is a characteristic of tin not shared by cadmium.

E. L. Moreland: I should like to ask if any comparative studies have been made of the relative wear on the contact wire of two contact shoes as compared with one contact shoe on a pantograph. There is a certain school that apparently is very definitely of the opinion that for a given current collection it is better to have two contact shoes, the theory being that a more continuous contact is maintained with the wire than would be the case with the single shoe.

On the other hand, there are some skeptics who say that a single shoe with light wire pressure would give less wear on the wire, and would give satisfactory current collection on multiple-unit cars where the amount of current to be collected per pantograph is relatively small, particularly at high speeds.

The only comparative tests I know of where equal mileage was run under the same conditions for 5000 miles each way, show that with the double shoe almost as much copper or bronze was lost from the contact strips on each of the two shoes as was lost from the single shoe. In other words, the pantograph with two contact shoes lost almost twice as much metal from the wearing strips as the pantograph with a single contact shoe running under the same conditions. That of course doesn't prove that the wear of the contact wire was in the same ratio, but it at least raises the ques-

tion as to whether the wear on a contact strip isn't in some measure an indication of the wear taking place at the same time on the wire.

My own feeling is that two shoes are probably the soundest for the flexibility they give, but these tests do amplify this question that I already had in my mind before I knew the results of the tests.

J. B. Cox: When the question of a contact device for the pantographs to be used on the electric locomotives for the original electrification of the Chicago, Milwaukee, St. Paul and Pacific Railroad was being considered, early in 1915, it was realized that the duty required would undoubtedly be more severe than had been experienced up to that time.

The Butte, Anaconda and Pacific Railroad had been in electrical operation for more than a year with 5-in. diameter steel tube rollers used for collecting the current from a single 4/0 trolley. It had been found here that while these rollers collected the desired current successfully, there was some sparking at hard spots in the line when only one pantograph was used, but that by using two pantographs in multiple this sparking was practically eliminated. Extensive tests were carried out at the Schenectady factory by rigging up a crank shaft by means of which various forms of contact devices might be caused to slide to and fro under varying conditions and pressures, with and without lubrication. During these discussions and experiments, many suggestions were offered, among which was the use of multiple contact wires with alternating supports.

I suggested the use of a double contact shoe for the pantograph, so interconnected mechanically as to cause the one to be held more firmly against the wire when the other was being forced from the wire by a hard spot or other cause.

Mr. W. B. Potter suggested, "Why not have both the double wire and the double contact, then there can be no reasonable doubt of being able to collect any probable amount of current necessary at any practical speeds that may be desired."

This suggestion was followed out, and special contact shoes designed with due provisions for the lubrication of the contact, which the experiments mentioned had definitely indicated, not only greatly increased the life of the contacts and decreased the wear on the wire, but also added materially to the current-collecting capacity of the pantograph, and reduced the sparking.

The results extending over a period of more than 14 years, have been quite satisfactory, and for similar types of electrification the practise has become almost standard.

Practically the same trolley construction and current collecting device was used on the Mexican Railway electrification.

In almost every instance of electrification, where steam locomotives have continued to be operated under the contact wires for any considerable length of time, there has been objectionable sparking for a few days, but this has always gradually disappeared as the deposit on the wire wore away.

The double contact shoe has been a great advantage in these initial operating periods, and even more useful when the wires become covered with sleet.

Some of the trolley wires on the Mexican Railway had been up more than a year before the electrification was put in operation, and the deposit on the wire from the steam locomotives caused

more severe sparking than I had seen before, and it continued for a longer time.

Double-unit locomotives were operated with two pantographs per unit up, thus making a total of four pantographs against the contact wires, which limited the sparking and at the same time hurried the clearing of the wire.

These experiences have led me to feel that there should be no doubt as to the advisability of using the double contact in any instance where heavy currents are to be collected at high speeds.

N. W. Storer: I agree entirely with what Mr. Cox has said about the advantage of the double shoe. The fact of the matter is we had some double shoes running on the Niagara Junction Railway on a 600-volt line while he was still figuring on the roller pantograph on the Butte, Anaconda and Pacific and other lines. They are necessary where heavy currents are to be collected and desirable for smaller currents in order to minimize the possibility of opening the circuit due to the shoe striking hard spots on the line.

W. B. Potter: I fully agree with what Mr. Landhy has said and with the remarks thus far during the discussion. So far as I have observed, it seems quite clear that the wear of the contact wire and collector is much more due to arcing than to the mechanical wear due to rubbing. Continuity of contact is essential if arcing is to be prevented and this can best be accomplished by such flexibility in both the contact wire and collector that they will react upon each other like opposing springs; the contact wire should, further, have no hard spots that might cause the collector to rebound.

Mr. Moreland has referred to the relative merit of the double and single pantograph collector. Both experimental tests and practise seem to prove that the double pantograph better insures the desirable continuity of contact. It will be of interest to mention an earlier installation, that of the Baltimore Tunnel in 1895 where the results were far from satisfactory. The overhead contactor was composed of two steel Z-bars with a plate over the top, the bars being far enough apart to leave a slot in the bottom. This steel structure, which corresponded to the contact wire, was catenary-supported. The collector was a block of bronze in the shape of a shuttle and weighed about 50 lb.; it had a tongue which projected through the slot between the Z-bars and to this tongue was connected the pantograph on the locomotive. The tunnel was rather wet and there was considerable accumulation from drippings within the steel conductor. During the initial operating the shuttle looked like a sort of traveling electric furnace,—ten to fifteen pounds of metal would be melted off during a single trip. The performance was improved by using a collector in the form of a steel scraper. The current was about 1000 amperes, and to collect this successfully without arcing then seemed well nigh impossible. The successful collection of several thousand amperes at 60 to 70 mi. per hr. has now proved to be a much simpler problem than was anticipated.

I. T. Landhy: With two shoes I think I can say from my own experience that you are more sure of contact on the contact wire. I have noticed sometimes that one shoe of the pair will be in contact and the other either barely touching or not at all, and if it were only barely touching with one contact shoe you would get burning along the surface of the contact strips as well as on the contact wire.

An Electrified Railway Substation Of the Pennsylvania Railroad

BY J. V. B. DUER¹

Fellow, A. I. E. E.

Synopsis—This paper contains a description of one of the outdoor substations of the Philadelphia-Wilmington electrification of the Pennsylvania Railroad, recently placed in service. It describes the initial installation of apparatus provided in the substation for the present suburban electrification, as well as the steps taken to accommodate the additional apparatus necessary for the through electrification when it takes place.

The location and control of the substation are described as well as

the types of protective apparatus utilized and the method of operation. Attention is called to certain operating necessities which control the design and location of a substation of this character. The means provided for handling the heavy apparatus into and out of a substation of this character and the facilities for handling, cleaning, and restoring oil to the different pieces of apparatus are described in some detail.

* * * * *

AS a preliminary to this description, it is necessary to state that the Philadelphia-Wilmington electrification at its present stage of construction is designed for the multiple-unit suburban service only, but that everything has been so constructed that expansion to care for the handling of through electric locomotive hauled service, both passenger and freight, may be accomplished by adding to the existing facilities, without necessitating the replacement of existing electrical facilities. For complete electrification of main line territory, four single-phase 132-kv. transmission circuits

commodates two single-phase transmission circuits, allowing for the sectionalization of each of these circuits by air-break motor-operated disconnecting switches. The structure further accommodates a tap from each of these transmission circuits, each of these two taps passing through another air-break motor-operated disconnecting switch to the high-voltage side of a 132/12-kv. step-down transformer, the tap being provided with choke coils and lightning arresters. The low-voltage side of each transformer unit is carried through a suitable two-pole oil switch and the requisite isolating switches to one section of a 12-kv. trolley bus. Ultimately, there will be four transmission circuits, four taps, (one from each circuit), and four transformers; but there will

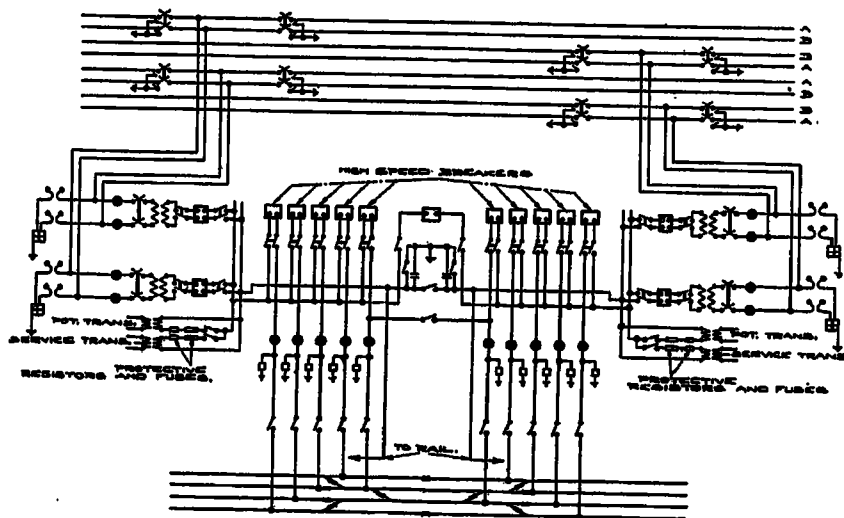


FIG. 1—TROLLEY SUBSTATION—WIRING DIAGRAM

on two tower lines are proposed; with four step-down transformer units at each typical trolley supply substation. The initial installation, for multiple-unit service only, has required but two single-phase 132-kv. transmission circuits, each on its own supporting structures; and at each typical trolley supply substation, but two step-down transformer units.

It is then evident that the existing typical trolley supply substation is a structure which at present ac-

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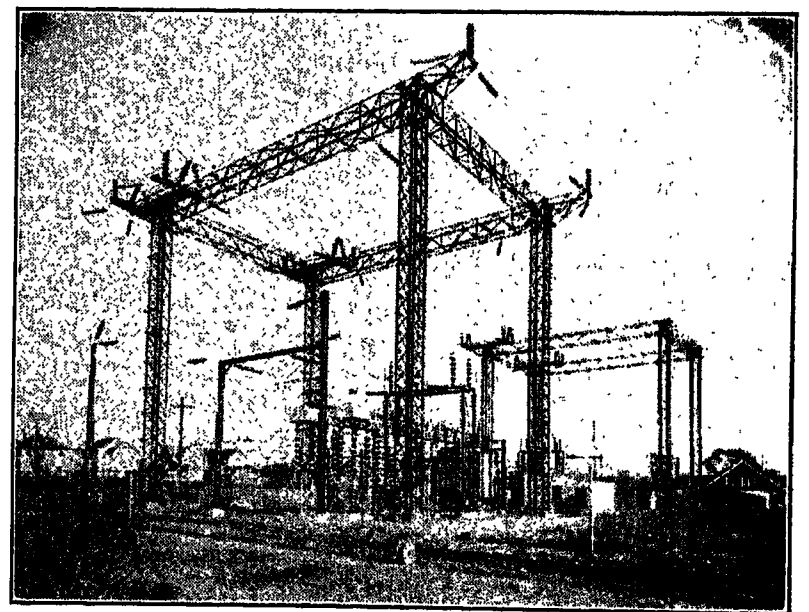


FIG. 2—TYPICAL TROLLEY SUPPLY SUBSTATION, GENERAL VIEW

be only two trolley bus sections, as at present, each with two transformers connected to it instead of one.

Each bus section consists of a trolley and a rail bus. The two trolley bus sections are connected through a suitable single-pole breaker and the requisite isolating switches. The two rail bus sections are arranged so that they may be connected together through disconnecting switches, and further, so that either section or both may be connected to actual ground if desired.

From the trolley bus section, taps are taken, each of which passes through a single-pole high-speed trolley circuit breaker and the requisite isolating switches to a trolley. The trolleys passing by the substation are sectionalized so that those on one side are electrically separated from those on the other side of the substation. The trolley bus taps from one section of the trolley bus feed the trolleys on one side of the substation, and those from the other section of the trolley bus feed the trolleys

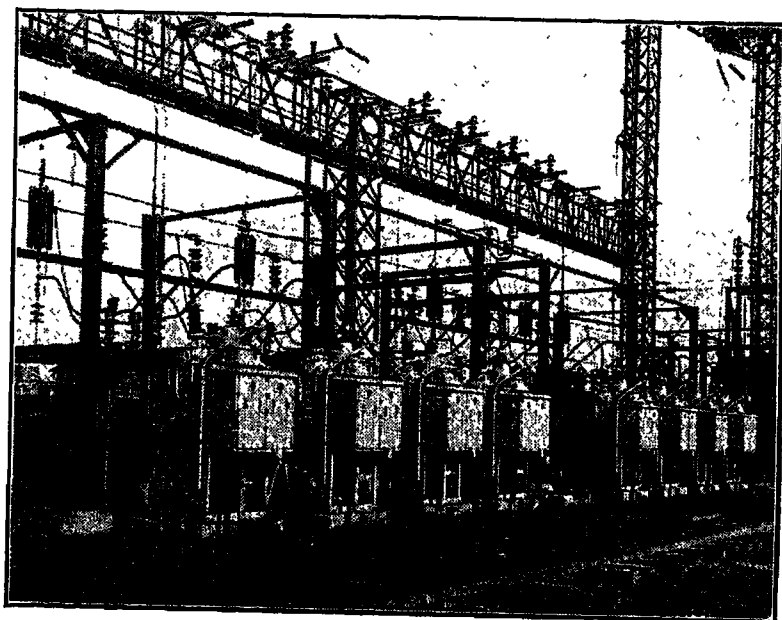


FIG. 3—TYPICAL TROLLEY SUPPLY SUBSTATION—TROLLEY BUS AND OIL CIRCUIT BREAKERS

on the other side of the substation. Each trolley bus tap is supplied with a choke coil and a lightning arrester and feeds into a different trolley from that fed by any other tap.

The railroad is equipped with interlocking cross-over

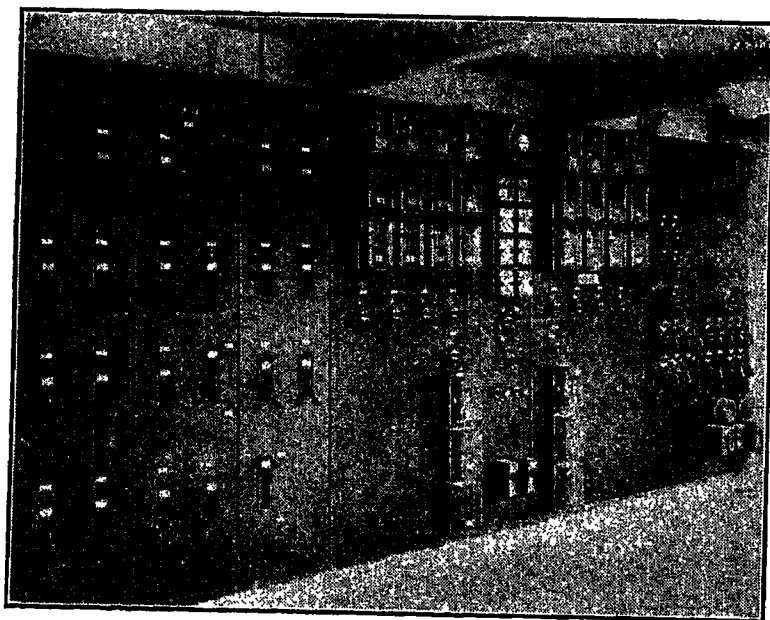


FIG. 4—TYPICAL SUBSTATION CONTROL BOARD IN CONTROL HOUSE

stations for the purpose of crossing traffic from one track to another at frequent intervals. These intervals are such that it is usually possible to locate the substations at certain of the interlocking cross-over stations. At one of these cross-over stations, the cross-overs between tracks are located between signal bridges, usually some 1200 to 2000 ft. apart. There is a signal and switch tower, more generally called an interlocking or block

station, with an operator to control the cross-over movements. This tower is connected with the dispatcher's telephone circuit and with the emergency telegraph circuit. There are usually certain signal maintenance men working in the vicinity of the block station. If the telephone circuit of the load dispatcher or power director be run into the block station, and if the block station be equipped with a control board and the necessary signal lamps, the operator can well perform such substation switching operations as the power director may request, keeping the proper record of such operations. Further, the operator can call by whistle or horn such signal maintenance man as may be within hearing and request him to perform such emergency operations within the substation as may become necessary prior to the arrival of a regular substation maintenance man. It is also evident that the trolleys covering the cross-over movements should be independently fed

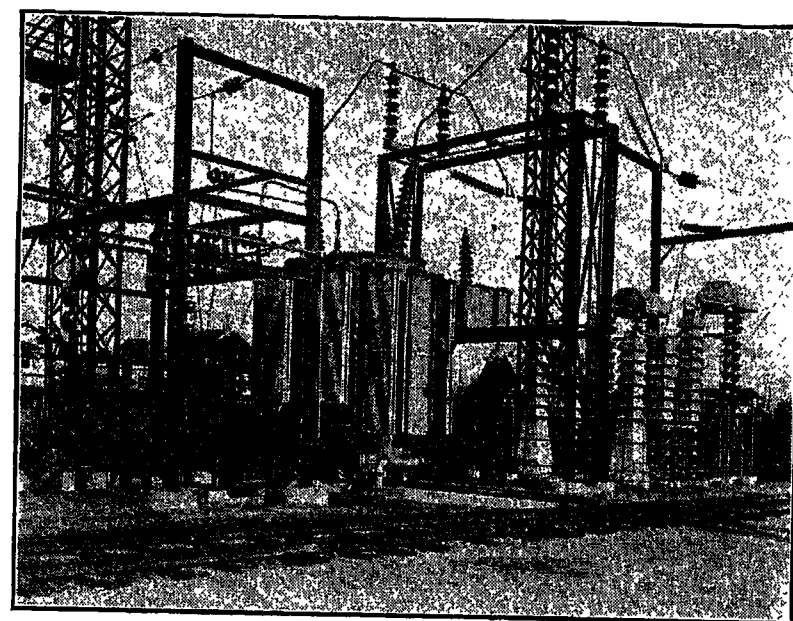


FIG. 5—TYPICAL TROLLEY SUPPLY SUBSTATION—4500-KV-A. TRANSFORMER

from those extending beyond, so that a dead trolley beyond will not hazard the making of a cross-over movement to another track to avoid the dead trolley. If the substation be located near the cross-over station, the cross-over trolleys may be readily fed independently, directly from the substation trolley bus sections. Cross-over stations not at substations require a special bus and switch arrangement to secure this independent cross-over trolley feed feature. We may state, therefore, that in so far as is possible, the typical trolley supply substation is located near a cross-over station and the substation switching operations are controlled from the block station by the block station operator under direction from the power director.

Within the fenced in enclosure of the substation is located a small control house. In this house there are located a control and relay board, a control battery and charging facilities, such signal supply motor-generator sets and switching as may be required, the substation oil treating plant with its purifiers, filters, and valves, and a telephone connected with the power director's circuit.

When the regular substation maintenance men are at work within the substation enclosure, by throwing a switch, they may take over the control of the substation switches from the block station operator's board to the control board in the control house. This operation is made upon direction from the power director and the block-station operator is informed and also receives a signal on his board when the control passes from his board to the control house board, or the reverse.

The entire relay layout for the station is on the control house board. All control operations and signals are at a control voltage of 125 volts, direct current supplied from the control battery. The control circuits are segregated for protection and for the easy location of grounds. Ground detecting apparatus is supplied.

In each substation are two service transformers, one on each section of the trolley bus, which give 230/115-volt, 25-cycle circuits from which the control battery is charged, the oil pumps operated, and the normal lighting obtained. A separate transformer supplies the signal motor-generator set or sets when such are installed at the substation.

Certain emergency lighting is supplied from the control battery.

Into each substation enclosure is run a railroad siding, and the apparatus is so located as to be readily loaded or unloaded to or from cars on this siding by a locomotive derrick or otherwise, as may be necessary.

The relay protection is such as to give the following protective functions:

Trolley high-speed breakers; high-speed impulse for short circuit; normal controlled speed relays for overload.

Each trolley bus section is differentially protected as to all breakers connected thereto for protection against bus faults.

Transformer breakers; reverse power protection for transmission line-to-line faults; differential protection for transformer faults. Voltage relays for transmission line to ground faults supplied from a 66-kv. potential transformer connected from the midpoint of the high-tension winding of the main transformer to ground, the step-up transformers at the station supplying energy to the high-tension transmission having their midpoint grounded through resistance.

Buried oil tanks are provided in each substation for both transformer and switch oil. The piping system is such that breaker oil may be drawn from a dirty oil tank and purified and run into a clean oil tank and run into a breaker. The transformer oil may be run from the transformer through the purifier and back to the transformer, or from the transformer into the tank and thence through the purifier and back to the transformer.

The oil purifier is a combined centrifuge and filter with provision for by-passing either or both, the latter for use when oil is drawn from the clean oil tank and passed to a breaker.

The step-down transformers necessary in our eastern territory for the eventual complete electrification are of 4500-kv-a. normal continuous rating, immediately followed by 150 per cent load for two hours, immediately followed by 300 per cent load for five minutes. Thus, these transformers are much larger than normal commercially rated units of the same nominal continuous rating. They are self-cooled and self-protecting and every attempt has been made to insure serviceability. The number of these units installed initially and ultimately in a typical Philadelphia-Wilmington substation has been previously mentioned as two and four respectively.

The above describes the requirements of the substation layout. The actual physical structure which fulfills these requirements need not always be the same. It depends, naturally, upon the land available and upon other considerations which influence its design.

Typical views of a step-down transformer station are shown.

Discussion

Sidney Withington: It may be of interest to note that on the New Haven, and on some of the other electrified railroads using substations of the same general nature as those discussed, each track on either side of the substation is fed from the same section of the bus, so that if a bus section goes out of service for any reason only one set of tracks is affected, that is, for instance, one continuous east-bound track, the west-bound track remaining unaffected past the substation. In the arrangement discussed by Mr. Duer if one bus section fails all tracks on one side of the substation may be affected unless (as of course is usually the case) there is feed from an adjacent substation.

Another point of interest in connection with the substation design is the high towers employed for the transmission line at the substations. It will be noticed in the illustrations that there is a very high fabricated steel framework for the 132-kv. feeders. There is undoubtedly a reason for that, and I think it would be of interest to bring it out.

An additional item of interest in connection with this substation design is the amount of ground employed. I think it is essential in all high-tension substations, to spread out the equipment so that not only is there plenty of room to allow safe work in an individual unit of equipment, but a failure will affect only a small part of the facility. It is obviously also a great advantage to have everything out of doors for the same reason.

H. C. Cross: Since Mr. Withington has asked two questions, I should like to answer them.

It is true, of course, in the trolley sectionalization scheme which we use that, if one-half of the station bus is lost, we cut the railroad in two, as it were, at that point; whereas Mr. Withington has at least two tracks on which traffic will automatically continue. However, if we do lose half the bus, the differential protection is such that there is practically only a momentary loss, that is, we are only cutting off power between two substations for a momentary time. I confess I do not know from the point of view of flexibility of operation, the exact reasons for the adoption of the scheme we use. It would appear to me to be more or less a question of judgment, in that since differential bus protection is provided there is no question of any serious hazard to the flow of traffic on the railroad.

The other question was about the height of the towers in the substations. If I am not mistaken that was very materially influenced by the striking distance of an arc from an air-break switch located below the 132-kv. transmission wires.

D-C. Railway Substations for the Chicago Terminal Electrification, Illinois Central Railroad

BY A. M. GARRETT¹

Associate, A. I. E. E.

Synopsis.—Direct-current substations designed to meet the demands of heavy railway terminal service are described in this paper. This direct-current energy is furnished at 1500 volts from seven substations located in the Chicago district and owned and operated by the power companies. In addition to 1500-volt supply for traction purposes, alternating current at 4000/2300 volts is provided for the railway company's light, power, and signal systems.

Approximately 80 per cent of conversion capacity is in synchronous converters and the remainder in mercury rectifiers. Reasons for selecting the latter units are given as well as some of the characteristic features of them.

To meet the rigorous requirements as to voltage and current demands under the agreement with the railway company, the conversion units have a rating of 300 per cent load for 1 minute.

The synchronous converters are of the field control type, and in

order to hold the d-c. voltage to definite values for any load within the rating of the unit and to maintain the reactive current of the unit within the safe limits, there is provided, common to all the converters in a substation, a counter e. m. f. regulating set, a 4-circuit rheostat, and a voltage regulator. High-speed air breakers are used on the d-c. side of the units and all 1500-volt feeders.

Another feature of interest is the use of truck mounted enclosed switch units on both the high and low tension sides of the substation. This type was selected in order to eliminate certain operating hazards which exist with fixed type switching arrangement, and to provide the customary factors of accessibility and maintenance.

In operating experience, the substation equipment has met all expectations, the performance of the synchronous converters and high-speed breakers being exceptional, while confidence in the mercury rectifier has not lessened.

INTRODUCTION

SEVERAL excellent papers upon the different features of the Electrical Terminal of the Illinois Central System have been presented to the Institute. The purpose of this paper is to describe that group of electrical equipment which comprises the substation, presenting the characteristics of this installation as a type representative of a d-c. application in modern railway practise.

These d-c. substations, owned and operated by the power companies, the Commonwealth Edison Company and the Public Service Company of Northern Illinois, receive the 60-cycle energy for conversion to direct current from the 12-kv. transmission system of the Commonwealth Edison Company and the 33-kv. transmission system of the Public Service Company.

To meet the exacting demands of heavy railway terminal service, the selection of the various electrical units and the arrangement of them in the substation layout followed along tried and proven lines. Yet consideration was also given to some equipment which, lacking at the time experience in the American field, gave promise of satisfactory adaptation to American practise through experience gained with the equipment in foreign use.

The studies, trial investigations, and test set-ups made jointly by the engineering staffs of the railway company, the manufacturers, and the power companies, gave a satisfactory solution of the various problems imposed by the standards of service, and these, coupled with the thought and experience of the power companies in furnishing conversion service for so many years to the traction systems of Chicago, were indispensable considerations in the design of the substation,

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Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

including not only the major converting and switching units, but the elements of connection as well.

SUBSTATION BUILDINGS

There are seven substation buildings in all, two of which are located outside the city in Public Service Company territory with the remaining five within the city limits. In keeping with the policy of both power companies these buildings are pleasing in architecture, substantial in construction, and of a style consistent with the best in the neighborhood. The buildings are one story and basement structures, arranged with more than the average space allotment per unit of equipment. Each bay, except the one for railway light and power equipment, is 24 ft. in width, which provides ample space around the main conversion units. This space is further increased by use of a converter of the consolidated type, in which the transformer and the converter are a single unit.

The use of enclosed switch units of the withdrawal type for both the incoming transmission lines, and the outgoing distribution feeders, requires additional space in front of each unit for pulling out the truck. Under normal conditions, this arrangement provides still more floor space or aisles on each side of the converting row.

Increase in the size and number of auxiliaries required with modern installations has demonstrated that a previous basement height of 12 ft. is inadequate. An increase to 14 ft. was therefore made. Increased headroom is also provided for the operating floor which allowed more liberal window space and pent house facility, thereby improving the light and ventilation.

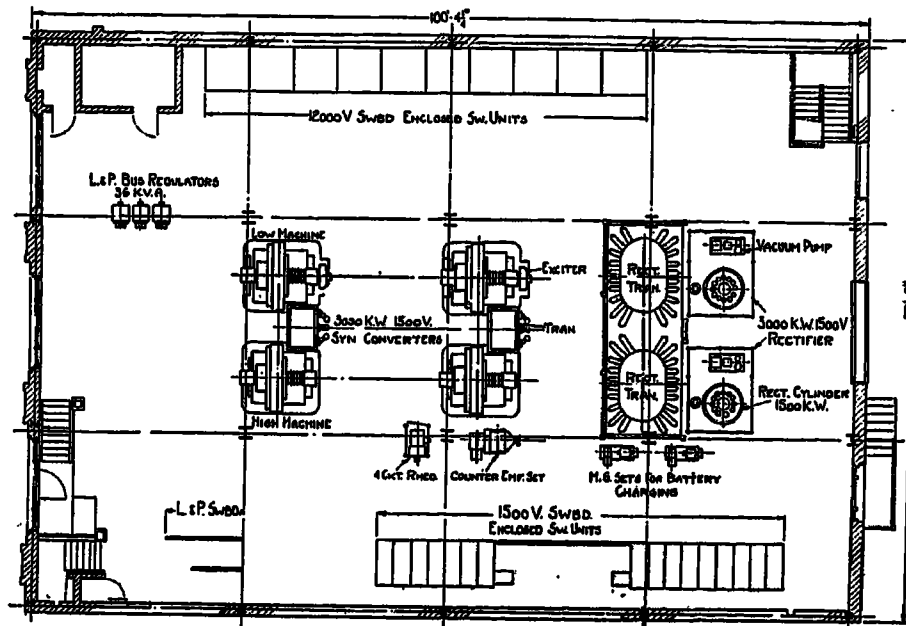
CONVERSION UNITS

To furnish converted energy under the current and voltage stipulation necessary to maintain the high rate of acceleration and high schedule speed demanded by the suburban service on this electrified terminal,

and to approximate these same duties under extra or congested traffic conditions, were the principal requirements that had to be imposed on the conversion units.

Over 80 per cent of the total conversion capacity is developed from 11 units of the rotating type, the synchronous converters, while the remainder is developed from 4 units of the stationary type, namely, the mercury converter or rectifier.

The decision to use rectifiers can be assigned to several



FIRST FLOOR PLAN—BROOKDALE SUBSTATION OF COMMONWEALTH EDISON CO.

reasons, principal among them being that this new type had the natural advantage which a unit with no moving parts has over one with rotating parts and wearable and friction surfaces, that it gave every indication through future development and application of meeting the demands placed upon it by American practise. Other reasons included the generally known advantages of the rectifier, high efficiency with fluctuating loads, absence of noise and vibration, low maintenance expense, and elimination of extensive ventilation facilities sometimes required with the synchronous converter. Also in this instance, a considerable amount of reserve capacity permitted the installation of a representative number of rectifiers.

SYNCHRONOUS CONVERTERS

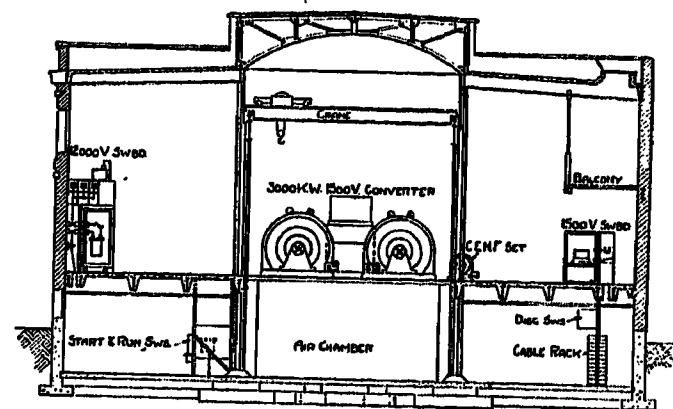
The synchronous converters, which are of General Electric manufacture, are furnished in 3000-kw. sizes with a d-c. voltage of 1500. Each outfit consists of two 1500-kw., 750-volt units operating in series. Each converter set is provided with a 3150-kv-a. air blast transformer arranged as stated before in a compact group by mounting the transformer on the bedplates of the a-c. side of the two machines. This served not only as a space reduction factor, eliminating the usual aisle of transformers lengthwise of the substation, but provides a short and convenient arrangement of a-c. leads between the transformer and the machine collector rings.

To meet the stiff voltage regulation required under

the agreement with the railway company, which permits a voltage variation within the narrow limits of 1400 to 1550 d-c. volts, together with the high drafts of current drawn by the system during the maximum rush hour, the converters are designed with a rating of 50 per cent overload for two hours, and 300 per cent load for one minute. They are shunt wound and of the field controlled type whereby the control of the d-c. voltage is obtained by changing the excitation of the unit and providing regulation by means of the reactive current drawn from the line or converter. Because of the reactive current involved, several limits as to rating were established so that overloading by the reactive current or the load current; or by both, would not exist. As stated previously the useful load output varies from 50 per cent overload for two hours to 300 per cent load for one minute, the corresponding rating for the reactive current output varies from 60 per cent reactive current at no-load to 30 per cent for the 50 per cent overload, and 50 per cent reactive for the 300 per cent load of one minute duration.

To keep the reactive kv-a. within the prescribed limits and hold the d-c. voltage to definite values for any load within the rating of the unit, there are provided common to all the converters in each substation, a counter e. m. f. regulating set, a 4-circuit rheostat, and a voltage regulator.

In order to maintain normal voltage conditions on the low-tension secondary connections to the rotary at times when there may be low primary or system voltage,



SECTIONAL ELEVATION—BROOKDALE SUBSTATION OF COMMONWEALTH EDISON CO.

or to increase the amount of the secondary voltage during periods of high load, the ratio of transformation between the high and the low side of the transformer may be changed in the ratio of 5 per cent by means of a tapped primary winding that is connected to two oil breakers, one of which provides a normal or 100 per cent voltage on the secondary side and the other connection 105 per cent voltage. That the load may not be interrupted when a changeover is desired, both breakers may be closed for a short interval to permit shifting from one tap to the other. These switch positions are known as the high and the low delta. In addition to this, the transformer is provided with a no-load tap changer on the primary side. Excitation

to the converter fields is furnished through a direct connected exciter operating on the shaft of the low-voltage converter. The exciter provides energy to the shunt fields of both machines at a fixed pressure, and each exciter and the shunt fields of the converters are connected in series to an excitation bus common to all the converter sets in the substation. Also to this bus

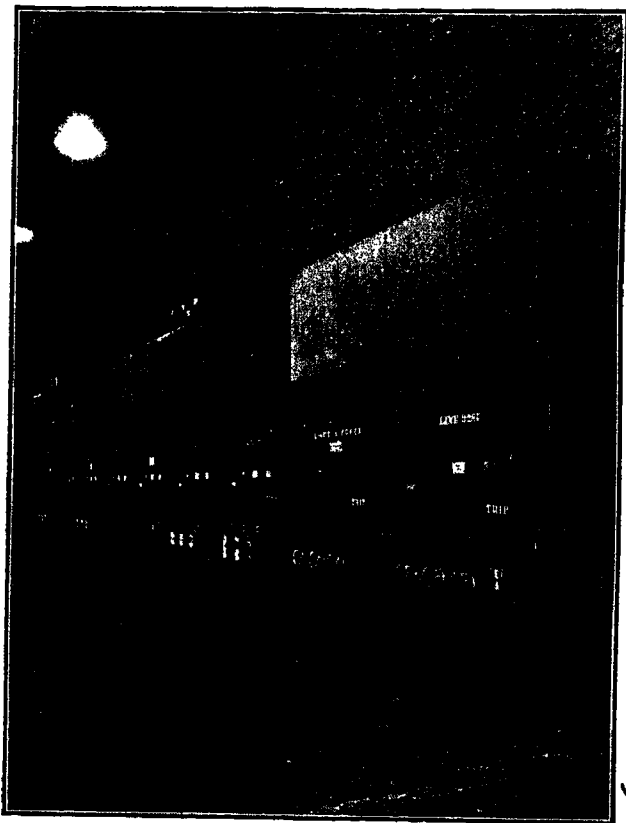
range of the *A* circuit varies from 15 per cent above normal to 35 per cent below. However, it is not felt these limits in the transmission system voltage will ever be realized.

The *B* circuit limits the minimum excitation of the converter fields so that the permissible reactive kv-a. will not be exceeded when high system voltage and low loads exist.

The *C* circuit operates to limit the amount of reactive kv-a. during periods of high load and low a-c. voltage. It has an auxiliary function of permitting higher values of reactive current on momentary loads above 150 per cent.

The *D* circuit, which is in series with the main coil of the Tirrill regulator, introduces resistance in the regulator circuit during periods of high a-c. voltage and loads below 40 per cent. This results in the regulator holding a higher d-c. voltage than actually exists, so that when a condition of no-load with high system voltage occurs the regulator will not tend to hold converter fields at minimum, as the load comes on, but will strengthen the fields with the increase in load. To do otherwise would increase the reactive current beyond the permissible limit.

The undercompounding coil of the Tirrill regulator provides the proper amount of regulation for the converter. With normal a-c. voltage this regulation is 1452 volts at 300 per cent load and 1525 volts at no-load.



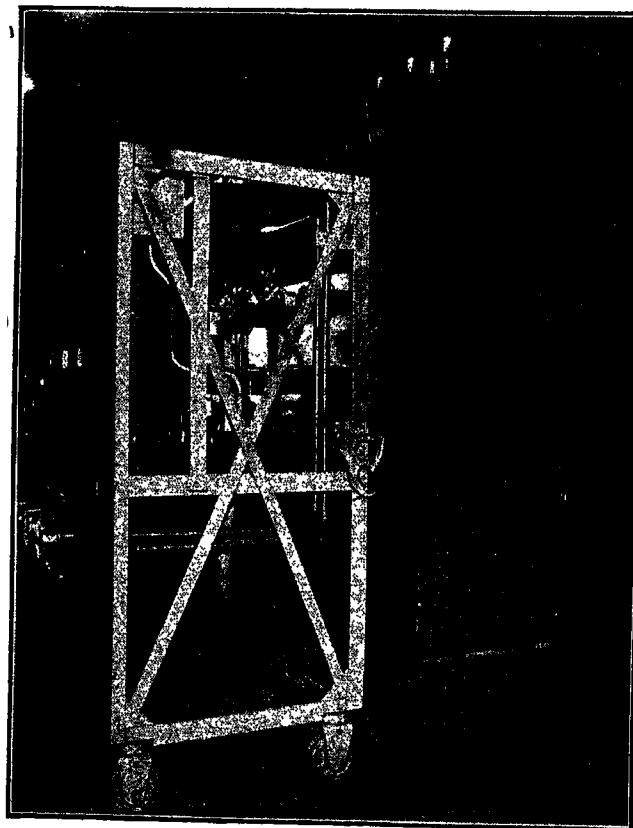
12,000-VOLT SWITCHBOARD (TRUCK TYPE—16TH STREET)

is connected the d-c. motor of the counter e. m. f. regulating set. This places the motor of the regulating set in series with each exciter and the shunt field of each converter and by varying the voltage of the motor, the voltage applied to the converter field is likewise changed or controlled. A field rheostat common to both shunt fields is provided and is used chiefly during starting periods, or when the regulating set is taken off and the converters are controlled by hand.

The function of the motor-operated, four-circuit rheostat and the Tirrill regulator on the d-c. side, is to control the operation of the converter and its regulating equipment under both normal and abnormal voltage conditions on the a-c. supply system in conjunction with the load and voltage conditions on the d-c. side of the unit; and to hold the performance of the unit within the prescribed reactive kv-a. limits over the full range of capacity.

Briefly, these four rheostatic circuits which are known as *A*, *B*, *C*, and *D* circuits, function as follows:

A circuit rheostat, which receives, through a potential transformer connected to 12,000-volt bus an indication of the voltage of the transmission system, controls or determines the entire setting of the rheostat through a rheostat arm that extends over the contacts of the other three circuits. If the voltage of the a-c. system is raised or lowered the arm of the *A* circuit changes, and establishes a new setting for the rheostat. The



12,000-VOLT ENCLOSED SWITCH UNIT

In those substations where the rectifiers have no regulating equipment, and the synchronous converters are operated in parallel with them, the d-c. voltage of the rectifier is in direct proportion to a-c. voltage and for successful paralleling the converter must have the same characteristics. This is accomplished by inserting a resistance in the undercompounding coil of the Tirrill regulator. By varying the amount of resistance, regu-

lation consistent with the voltage drop of the rectifier is obtained.

The converter which has a speed of 600 rev. per min. is started by the Y-delta method. The unit operates off the 12-kv. bus through 4 oil breakers; the running switch, an automatic breaker of high interrupting duty, the Y and the high and the low delta breakers, the last three being non-automatic and of the ordinary type of frame or panel mounted oil switches.

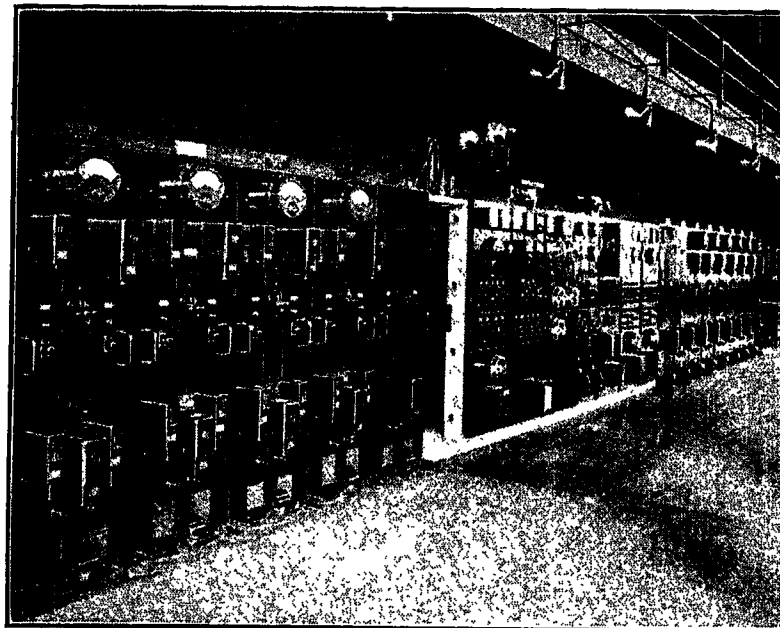
Each converter is connected to the 1500-volt d-c. bus through 3000-ampere high-speed circuit breakers of the bucking bar type located in both the positive and negative leads. The positive breaker, which is located in a metal enclosure on the operating floor, is arranged to trip in case of a reverse current arising either from faults within the unit, or on the transmission system. The negative breaker, which is the more active of the two breakers, takes care of overloads or short circuits in the forward direction, that is, those overloads or disturbances occurring on the 1500-volt bus or feeder system.

The negative breaker is provided with an automatic reclosing feature in case the overload or short circuit is cleared within a predetermined time. When the breaker opens a current limiting resistor is inserted in the circuit. The voltage drop across this resistor is inversely proportional to the resistance of the external fault. A ground or fault of zero resistance impresses a voltage of 1500 across the resistor. A time delay relay, which comes into action when the breaker opens, causes the negative to remain open and trips the positive breaker if fault condition persists for a definite length of time. This breaker, which is selective with the high speed breakers on the 1500-volt feeders, is located in open frame mounting in the basement in close proximity to the negative leads and bus. Other protective devices consist of a speed limit switch for overspeed protection and a ground or flashover relay, both of which trip all breakers connected to the unit. In addition to the protection against commutator flashing by means of the high-speed breaker, guards and arc chutes or hurdles are placed on the commutator between brush arms to break up and dissipate the flash, thus preventing its spread from bar to bar across the face of commutator.

MERCURY RECTIFIERS

Four of the substations contain mercury rectifiers of the iron tank type. Three of these units operate in parallel with the shunt converters described above. Two of the units are of 3000-kw. size, each consisting of two 1000-ampere, 1500-volt rectifiers operated as a single unit. These sets, which are of Brown Boveri manufacture, have separate transformers and under-load tap changers but are connected to a common oil breaker. The water cooled rectifier tank is connected to the double six-phase windings of the transformers. This arrangement provides for 12 anodes which are

equipped with air cooled radiators. The water consumption at rated load is approximately $\frac{1}{3}$ gallon for 100 amperes of load per minute. The units are designed to carry 50 per cent overload for 20 minutes and 300 per cent load momentarily. Each bowl or rectifier is provided with an ejector or mercury vapor pump and a single stage rotary oil pump, both for the evacuation of gases from the interior of the rectifier. The mercury vapor pump, a stationary device, which operates on the injector principle, is actuated by an electric heater located in the base of the pump.



1500-VOLT SWITCHBOARD (TRUCK AND PANEL TYPE) 16TH STREET

The vacuum, or conversely the pressure of gases within the unit, is measured by balancing the gases against a column of mercury known as the McLeod gage. A means of more quickly identifying conditions within the bowl is obtained by the direct reading vacuum meter. This device consists essentially of a hot wire gage operating on the Wheatstone bridge principle arranged so that two of the arms of the bridge are subject to the gas pressure within the rectifier while the other two are exposed to the pressure of the atmosphere; the difference in resistance due to difference in pressure causes a current to flow through the vacuum meter which is calibrated to indicate the vacuum directly in millimeters of mercury.

All seals within the unit are made with mercury, asbestos, or by rubber gaskets. The unit is connected to the 1500-volt busses through a high-speed breaker placed in the positive lead of each cylinder. This breaker is of mechanical latched type, designed to operate on overload or short circuit which may occur in either direction.

The air breakers are interlocked with the oil breakers so that in case the oil breaker opens from overload or short circuit, the air breaker opens also. The rectifier is provided with relay equipment designed to take the unit off the service if excessive temperatures are present within the rectifier cylinder.

The rectifier with the transformers, which are of the

oil-filled and self-cooled type, take the ordinary floor construction customarily found in station and substation structures. However, no conservation of space is found with the rectifier, the floor area occupied by the rectifier being equal to that of the synchronous converter. Absolutely no noise of operation is associated with the rectifier proper. Some noise will be found in the rotary pump but none that cannot be mitigated to any desirable degree.

The 1500-kw. rectifiers are of General Electric manufacture, two 500-ampere cylinders operating in parallel from a single transformer and oil breaker. Each cylinder consists of 6 anodes of graphite composition and is provided with wire wound heaters to keep the anode insulators at proper temperature during periods of external low temperature and low loads that mercury will not condense on them. The water-cooled chamber is supplied with heaters for the same purpose. To reduce possibility of high transient voltages appearing on the rectifier, condensers in the form of power capacitors are connected to one set of three anodes and across the interphase transformer. That the load will divide equally between the bowls, anode reactors are provided. These rectifiers have practically the same other protective features as the 3000-kw. units, except that following the same design provided for the General Electric converter, high-speed breakers of the bucking bar type are placed in the positive as well as the negative lead of the rectifier. These units have a rating of 50 per cent overload for

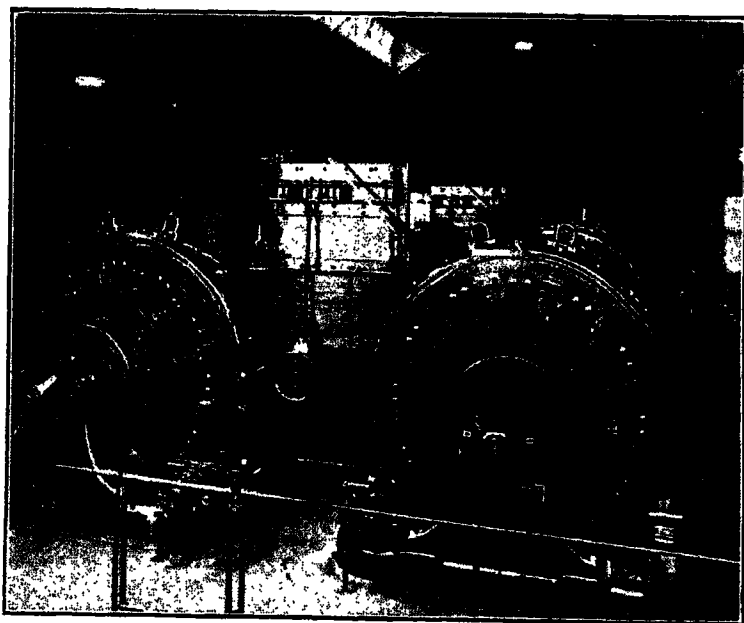
connecting devices truck mounted and enclosed in metal housing.

The use of the enclosed switch unit is not a new idea, having been on the market in various forms for some considerable time, but its application to both high- and low-tension switching in the same substation is somewhat unusual. The point of principal interest in these installations, however, is the application of the switch unit to certain ideas gained from the operating and engineering experience with other switching arrangements. By means of interlocks it prevents that kind of operating hazard which seems to be always with us in the old style of fixed bus and switch structure, namely, that of pulling disconnective switches while under load. The switch unit makes readily accessible for maintenance, repairs, and inspection all of the wearable, adjustable parts. Not only is factor of safety improved but, because of the accessibility, better maintenance and repair work is done and therefore better performance is obtained.

Certain operating practises entirely practical with 600-volt switching equipment are not acceptable when the pressure has been increased to 1500 volts or above. Correction by isolation, through elevation, may not always be desirable or lack of clearance may render the arrangement impractical, therefore the use of the switch unit, with the added advantage of accessibility, is in many cases a solution entirely satisfactory. The advantages accruing to the truck mounted breaker is considerably lessened when it is necessary to unbolt, and in many cases untape, the breaker connection from the fixed conductors within the structure. The use of the automatic disconnect for both the current-carrying circuits and the control circuits does away with the unwieldy, and in many instances dangerous, method of manual disconnection. The principle of pressure-contact disconnects can be used in many truck designs so that danger and bother from overheated disconnect switches is appreciably reduced.

By the enclosure of the individual switches in separate metal compartments, the tendency of the arc to spread in case of breakdown, is greatly reduced over those cases which have occurred in the open fixed type of structures. Confining the arc to one or two immediate compartments is quite different from the trouble experienced in the old design where the entire structure and sometimes the room become involved from one breakdown.

The incoming transmission lines, bus tie connections, and connections to the individual conversion and transforming units within the substation are connected to the 12,000-volt busses through 3-phase, 15,000-volt, 600-ampere, type O.E. 6 oil breaker of Westinghouse manufacture. The breaker, automatic disconnects, and hand-throw disconnects are carried in a panel mounted truck, the panel serving the double purpose of closing the cell compartment and providing the switchboard facility for all instruments, relays, control



3000 Kw., 2 UNIT CONVERTER (16TH STREET)

20 minutes and 300 per cent load momentarily. The inherent regulation of the rectifier is approximately 5 per cent.

SWITCHING FACILITIES

Another feature of interest in these substations, especially those which are supplied from the 12-kv. system, is the design and arrangement of switching equipment on each side of the conversion units. Fundamentally this consists in having the breakers and dis-

switches, and interlocks. The principal features of this type of iron clad switch gear, are that nothing electrical is accessible until the breaker is in the open position and that when the truck is withdrawn live parts are shuttered off or set back in protecting recesses. In addition to these features the switch unit is provided with manual operated knife disconnects which permit all grounding operations to be made through the oil breaker, an operating practise which has been in force in the substations of the power company for many years. The grounding of any line, bus, or unit directly through cable, clamp, and knife switch devices means that the operator when the last connection of the circuit is made to a ground source, must be in immediate proximity of a fault to ground should an operating error be made. The simple method of making any set of disconnects, used in conjunction with a breaker, doublethrow, with the one side connected to a ground bus permits the operator to be at a safe distance when the last link in the ground connection is made (closing the oil switch) and also provides relay protection should an error exist and live circuits be grounded.

This equipment is arranged so that an oil breaker can be partially drawn out of the cell for inspection of the parts, at the same time leaving the control intact for operation of the breaker but cutting off contact with all live high-tension connections. This group of breakers and housings is properly insulated for later installation of a fault bus system should one be found necessary. For the two substations located outside the city and operated by the Public Service Co., the 33-kv. switching equipment and bus including the transformers of the converters and rectifiers is located out of doors adjacent to the substation building. The high-speed air breaker connected to the positive lead of the conversion units as well as all the breakers on the feeders are truck-mounted and enclosed in metal compartments similar to the switching facilities for the 12,000-volt equipment. The 1500-volt bus is also enclosed in same metal housings. The principle and characteristics of this breaker and its application to the 1500-volt distribution system of the railway terminal have been presented to the Institute by Messrs. Monroe and Allen.

In order to avoid the inconvenience of testing high-voltage instruments, the watthour meters which measure the 1500-volt output energy of the converting units are installed in the negative lead of the unit in every instance except one, this being at the Front Avenue Substation where 1500-volt energy is also delivered to the Chicago, South Shore, & South Bend Railway Company.

One bay of each substation contains the transformers, regulating and switching equipment for the a-c. supply to the railway company light, power, and signal systems. Energy is taken off the 12-kv. bus and stepped down to 4000 volts for the 3-phase 4-wire railway light and power system and the 2300-volt for the single-phase signal system. As the signal system is ungrounded, an insu-

lating transformer of equal ratio is provided in the supply to the signal system. All the energy to the light, power, and signal systems is regulated. The switching equipment regulators, methods of installation, etc., are of the customary type found on a-c. distribution circuits. Space is provided in the substation for an extension of this equipment when necessary.

OPERATING EXPERIENCE

The synchronous converter without exception has shown a remarkable performance not only in the matter of regulation but under short-circuit conditions in which the number of flashed commutators has been practically negligible. Successful parallel operation with the mercury rectifier has been proved at all ranges of load.

Taking the group of mercury rectifiers as a whole, it cannot be said that our confidence in them has lessened. On the contrary, the operating experience shows that a great number of them could have been installed. For this class of service it has been demonstrated clearly that the use of one rectifier in a substation, operating as a base load unit with the converters reserved for the peak loads, results in a most satisfactory combination. In some instances a certain amount of trouble on the rectifiers can be charged to an overload condition as the earlier type of lacked capacity comparable with that of the synchronous converter operating in the same substation.

In general, the rectifier under normal operation has shown such gratifying results and advantages and with recent improvements made upon the unit and its auxiliaries indicates a reliability practically equal to that of the synchronous converter.

The performance of the high-speed breaker has been exceptional, especially in preventing the spread or reflection of short circuits back into the substation.

The light, power, and signal systems, outside of some trouble initially, have given none.

In common with the opinion given of the operating experience of the entire terminal, as expressed in a previous paper, that "From every point of view the equipment has met all expectations and the complete operation has apparently been successful," the operating experience of the substation equipment has indicated a similar result. Troubles have occurred as they naturally do on systems of this magnitude, but in no instance has anything happened that seemed impossible of solution, and in most cases immediate remedies have been found.

Discussion

D. C. Jackson: I am convinced that the 3000-kw., 3000-volt rectifiers that we are planning to install in the substations of the Lackawanna Railroad are going to prove satisfactory and economical conversion devices. The rectifier has had relatively little service in this country, but large service in Europe. It is an important new instrument in heavy railroad electrification and I think we will hear much more of it. Mr. Garrett speaks of it somewhat cautiously but at the same time indicates a degree of confidence in it which in my opinion is justified.

Sidney Withington: I agree thoroughly that the mercury rectifier is going to be extremely important in connection with any d-c. railway electrification. It would be interesting to know whether any special devices are employed to insure the proper division of load between the rotary converters and the static rectifiers.

W. B. Potter: I believe the rectifier will largely take the place of rotary converters and motor-generator sets on d-c. railways, and to some extent for lower voltages where the conditions are more favorable to stationary apparatus.

I believe the future for railway electrification, about which we have talked so many years, is beginning to look brighter. The steam locomotive engineers are improving the performance of the steam locomotive to such an extent that ere long we may anticipate a demand for even better service than can be furnished by the electric locomotive.

A. M. Garrett: There are eleven or twelve rectifiers in operation now in the Chicago district, and probably double that number immediately outside in Northern Indiana and in Milwaukee.

Professor Jackson raised the question of whether we weren't too cautious in our opinion of the rectifiers. Our experience with rectifiers has shown three things: First, in connection with the phenomena of the electric arc, we have much to learn regarding what takes place inside the unit not only under normal conditions, but abnormal conditions as well. The second point is whether we are reaching a limit in the rectifier as applied to American practise. The rectifier "grew up" in foreign practise and we feel that the systems back of them in Europe, differ from those in this country. Here there is a tendency to hold everything on

the bus. In Europe, I understand it is a case of disconnecting to keep the individual lines alive. A third point is whether we can apply improvements to the rectifier that will make it comparable in every respect with the rotating converter.

With rotating converters there are certain problems which have never been solved in connection with brushes and commutators. The rectifier offers a solution to many of those problems. Furthermore, the fact that it is a static machine gives it a marked advantage over a rotating type.

The point was raised of paralleling the rectifier with the converter. In one substation where there is both a converter and a rectifier, where the units might be called upon to operate with a 300 per cent load with voltage limits between 1550 and 1400, it was felt that some special provision should be made for paralleling. A regulator was installed but satisfactory performance can be had without it.

We have two 600-volt rectifiers in operation now in the Chicago district, 3000 kw., 600 volts. They give good service.

At times the adverse of performance of rectifiers has been marked but we believe with certain improvements very good service can be expected from them. For a city traction system where one unit per substation is used and the substations are located frequently along the routes so that load transfer from one to the other may be provided, the rectifier is very well adapted.

The rectifier shows up very well where mitigation of noise is necessary. In residential districts a rotating machine must be enclosed to keep the noise down. The rectifier on that one score alone shows to marked advantage.

Master Reference System for Telephone Transmission

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Synopsis.—The telephone transmission system described here is the Master Reference System of the Bell System for the expression of transmission standards and the ratings of the transmission performance of telephone circuits. The transmitter and receiver elements of this system are reference standards for the ratings of the transmitting and receiving performance of terminal station sets.

A replica of this reference system, installed in Paris, has been

adopted as the Master Reference System of the International Advisory Committee on Long Distance Telephone Communication in Europe. The establishment of these two master systems provides a common reference for the telephone transmission work of the Bell System and the telephone administrations which are members of this International Advisory Committee.

THE Master Reference System for Telephone Transmission, as its name indicates, is to serve as the fundamental circuit in the ratings of the transmission performance of telephone circuits. In describing this system, therefore, it will be advantageous to outline first the general considerations underlying the methods of determining and specifying these ratings and their applications.

The conversions and transfers of energy which constitute the process of telephone transmission result in general in a difference between the speech sounds at the sending end of the telephone circuit and the sounds reproduced at the other end in the ear of the listener. These reproduced sounds may differ from the original in three important respects: their loudness, their distortion or degree to which their wave shape departs from facsimile reproduction, and the amount of extraneous sound or noise which accompanies them. From the standpoint of telephony, the major importance of a difference between the original and reproduced sounds is determined by its effect on "intelligibility," that is, the degree to which the latter sounds can be recognized and understood by the listener when carrying on a telephone conversation. The tolerable departure of the reproduced from the original sounds is limited also by certain effects which are noticeable to the listener before they materially affect intelligibility, such as loss of naturalness.

Measurements of intelligibility are of utmost importance in rating the performance of telephone circuits, but they are unduly cumbersome for direct use in the detailed development and design of telephone circuits and their many parts, particularly where small effects are concerned. It has been desirable, therefore, to handle telephone transmission work in two steps. One natural division is suggested by the statement that intelligibility is a function of the relation between the output and input speech sounds, and of the psychological reaction of the listener to these output sounds.

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Because of the complex nature of the speech sound waves, however, it has been found more practicable to treat the transmission performance of telephone circuits in the following two parts: (1) the physical performance of the circuit, and (2) the relation between physical performance and intelligibility. The physical performance of a circuit is taken here to cover the transmission characteristics which can be specified in terms of the performance for single frequencies, a number of frequencies being taken to cover the range which is important for the reproduction of speech sounds. These measurements of physical performance cover such things as the response-frequency characteristic of the circuit over the range of speech frequencies, the distortion due to non-linear elements, phase distortion, and the extraneous currents which cause noise. These determinations of physical performance do not include measurements of the speech sounds themselves, nor of the functioning of the talker and listener. This differentiation is advantageous in segregating the studies of speech sounds and of the psychological phases of the work, and permits the design of the operating plant and a large portion of the development work to be carried out on a physical basis.

The determination of the relation between intelligibility and the physical performance of a telephone circuit is a laborious process, because persons play the parts of generators and meters and a number of people must be used in both parts to take into account the normal ranges of their performance. The goal of this portion of the work has been, therefore, to establish suitable relations which will permit the determination of the intelligibility of a circuit by computations which start with the physical characteristics of the circuit. This work¹ has involved determinations of the capabilities of circuits having various kinds of physical characteristics to reproduce intelligible speech, investigations of the nature of speech sounds and hearing, and of people's customs in using the telephone.

Prior to the time when suitable means were available for measuring the physical performance of telephone circuits, and when the kinds of circuits in commercial

1. For all numbered references see end of paper.

use were quite similar in their distortion characteristics, the practise was adopted of rating the performance of a circuit by comparing it on a loudness basis with a reference circuit which was adjustable in attenuation, and whose distortion was closely similar to that of the commercial circuits. In such a comparison, a determination is made of the equivalence of loudness or volume of these two circuits by talking alternately over them and adjusting the reference circuit until the sounds coming out of the two receivers are judged to be equal. For the conditions where volume is the important controllable characteristic of telephone circuits, these loudness comparisons constitute a practicable and effective means of indicating the performance of these circuits.

The reference circuit adopted about twenty-five years ago for these loudness comparisons consisted of transmitters, receivers, station sets, cord circuits and a line, of types which were then used commercially. In this reference circuit the line was an adjustable artificial line simulating a No. 19 A. w. g. cable circuit having a capacity per loop mile of $0.054 \mu f$. The amount of cable in this line to give a loudness balance was taken as the rating of the circuit under comparison. This reference system, shown schematically in Fig. 1, has been called the Standard Cable Reference System.

In addition to this rating of the performance of a telephone circuit, this standard cable reference system has had other applications. Certain settings of this reference system were selected as specifying the standards of transmission which were to be provided in the design and operation of commercial circuits for the several kinds of service, such as local and toll. The effect of introducing or changing any part in a commercial circuit was rated in terms of the amount of cable by which it was necessary to change the line of the reference system to produce the same effect on the loudness of the reproduced speech sounds. Likewise, the transmitters and receivers of this reference system were used as reference instruments for the comparison and rating of other transmitters and receivers.

This cable reference system has played a very important and necessary part in the development of telephone transmission, in that it has provided a ready means of rating the performance of the various parts of the system and of any changes, and made it possible to design commercial circuits to provide a predetermined grade of service. The performance of this system was specified by stating the kinds of apparatus and circuits used. The performance of the elements of the electrical portion of the system could be checked by voltage, current, and impedance measurements, but for the transmitters and receivers reliance for constancy of performance was placed primarily upon the careful maintenance and frequent cross comparisons of a group of transmitters and receivers which were specially constructed to reduce some of the sources of variation in the regular product instruments. In this

way, reasonable assurance of the performance of the reference system was secured. This system has been widely used both in this country and in other parts of the world, and the performances of the various systems have been kept in accord by frequent circulation of calibrated transmitters and receivers.

As the telephone art has developed, modifications have been found to be desirable in this reference system to make it more suitable for its purpose. Telephone instruments and circuits have been designed and used which have less distortion than existed in the corresponding parts of the cable reference system. For this reason it is desirable to have as a new reference system one with which the transmission over the most perfect telephone circuit or over some less perfect one may be simulated at will. The change of the unit of transmission from the mile of standard cable to the decibel² has brought about the need for a change in the line of the reference system.

In selecting a new reference system, it is obviously desirable to eliminate as far as possible the factors

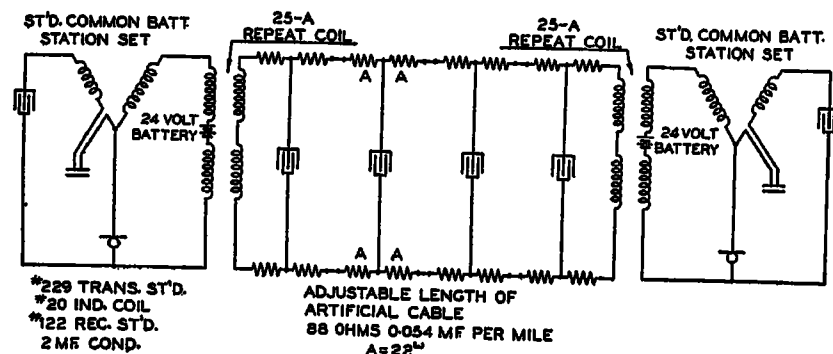


FIG. 1—STANDARD CABLE REFERENCE SYSTEM

which are not subject to exact measurement, or which may possibly vary with time. For this reason, the elements of the new system have been chosen so that their performance may be definitely measurable at any time, and may remain as far as possible invariable. This applies also to those elements which are provided for insertion in the system when it is wished to produce some distortion which will make more easily possible a loudness balance between the reference system and the circuit under investigation.

A reference system such as that described here, in which the essential elements are so constructed as to reproduce speech with a high degree of perfection, and with which provision may be made for modifying the speech in definite and reproducible ways, affords a convenient means for studying the capabilities of telephone circuits of different physical performances. These investigations, however, are outside the purpose of this paper, which is to describe the new reference system and its application in making volume ratings.

GENERAL REQUIREMENTS

The outstanding conception of the new reference system is that its performance should be suitable to serve as a reference base line for indicating the performance of all telephone circuits and that the trans-

mitter and receiver elements of the new system should provide similar base lines for the performance of electro-acoustic converters. To meet these needs properly the performance of the system and its parts should be capable of being measured and definitely specified in terms of physical quantities. In this connection, there arises a matter which has been the subject of much discussion, namely, as to whether or not the specified performances of the reference transmitter and receiver should be those which are realized when used as telephone instruments. In regard to the transmitter, the difficulty comes in specifying the input when it is placed in front of the mouth of the talker. This is due to the non-uniformity of the sound field from the speaker's mouth, the nature of the waves of speech sounds, and the reflections of these waves from the transmitter. In regard to the receiver, the difficulty is due to determining the output when the receiver is held to the ear. To obviate these, it has been decided to specify the performance of the transmitter in terms of the electrical output for a given pressure on the diaphragm of the transmitter and of the receiver in terms of pressure set up in a simple closed chamber for a given electrical input to the receiver. These conditions are definite and reproducible.

The most important requirement, then, for the reference system is that the physical performance of the system and of its component parts should be capable of being measured and definitely specified in terms of physical quantities. If this requirement is realized, a system providing the specified performance can be set up wherever desired. This has been the main criterion in the design of the master reference system for telephone transmission which is described here.

The second main requirement is that specifiable and predeterminable changes can be made with respect to the performance which is selected as the reference. These changes must be capable of varying the relation between the loudness of the reproduced sounds with respect to the initial sounds, the distortion of the wave shape of these reproduced sounds, and also the amount of noise accompanying these reproduced sounds.

For convenience in specifying these requirements, it has been found desirable to impose another requirement, namely, that the system be capable of giving a performance which is as free as possible from distortion and noise. It should be noted that two kinds of distortion must be taken into account: that due to unequal efficiency for sounds of different frequencies and that due to non-linearity causing unequal efficiency for sounds of different magnitudes. This requirement is also of advantage in insuring that the reference system and its parts will have less distortion than any circuit or instrument with which it may be compared. This will permit the simulation of the distortion of such instruments or circuits by the insertion of distortion in the reference system.

For convenience in use, it is highly desirable that the performance of the reference system and its parts

be constant for a reasonable time under normal operating conditions.

GENERAL FEATURES

The master reference system³ employs a transmitter and receiver which are capable of a high degree of freedom from distortion. The transmitter is of the condenser type and the receiver is of the moving coil type. Both these instruments are materially lower in efficiency than commercial types of apparatus, but this condition is compensated for by the use of multi-stage vacuum tube amplifiers. These instruments, together with their associated amplifiers, constitute reference standards for converters between acoustic and electrical energy. The third necessary element of a telephone transmission system, namely the line, is provided by a network of resistance elements. Such a line can be made to provide uniform attenuation over a wide frequency range, and can be made to control the magnitude of this attenuation over a large range. This line is taken as giving a reference performance for lines.

The specification of the performance of such a system is based on the principle of the thermophone, which is a converter of electrical energy into acoustic waves by means of the heat generated by the passage of an electrical current through a resistance. From a knowledge of the form and physical constants of this resistance element, of the medium in which it is used, and of the electrical input to the element, the acoustic pressure generated in a chamber of known size can be determined by theoretical considerations.⁴ The performance of the condenser transmitter is determined by making its diaphragm a wall of a simple closed chamber in which the thermophone is placed. By this means a known pressure wave of any frequency over the range desired can be impressed upon the diaphragm of the transmitter. The voltage output of the transmitter for a specified circuit condition is then measured. From this measurement, the ratio of the voltage output to the acoustic pressure on the diaphragm is established for that instrument and circuit condition. With the performance of the transmitter thus established, the performance of the receiver element of the reference system is measured by acoustically coupling the receiver to the condenser transmitter, so that the receiver actuates the transmitter, and then determining the relation of the pressure generated by the receiver in the coupler to the voltage input to the receiver. The performance of the line element is determined by well known means. The performance of the whole system can then be expressed in terms of the pressure produced by the receiver with respect to the pressure on the diaphragm of the transmitter.

The performance of this system is practically free from distortion for the energies which it is required to handle, and probably materially excels in this respect that of any previous system. With this system, volume relations between output and input sounds can be varied over a wide range with practically no accompany-

ing distortion. In comparing such a system, however, with commercial systems, it is advantageous also to be able to control distortion. This is particularly the case when using the instruments of the master system for rating the volume efficiency of commercial types of transmitters and receivers. To facilitate this, arrangements are made for the introduction into the amplifiers associated with the transmitter and receiver, of networks which may be designed to give a variation of efficiency



FIG. 2—MASTER REFERENCE SYSTEM FOR TELEPHONE TRANSMISSION WITH ASSOCIATED CALIBRATION APPARATUS

with frequency which corresponds to that obtained with commercial apparatus. These networks and their distortion effect can, of course, be definitely specified. The line element of this master system can be replaced by a line or network giving any type of distortion desired. Also, known amounts of extraneous currents to produce noise can be introduced into this circuit without otherwise appreciably affecting its performance. This is accomplished by connecting a relatively high impedance source of voltage of the desired wave shape across a circuit element of relatively low resistance.

This system provides a performance which is definitely known, and which can be varied over a range of volume and distortion. It well meets the requirements and represents a material advance over the standard cable reference system which it now replaces. In order to tie together ratings established in terms of the old system with those of the new system, comparisons of the two have been made to determine the adjustments of the new system which make its loudness performance correspond with that of the old.

DESCRIPTION OF MASTER REFERENCE SYSTEM

The master reference system with associated calibration apparatus is shown in Fig. 2. This equipment, mounted on steel panels and racks, and arranged as shown, is installed in a room, shielded from acoustical and electrical disturbances, at the Bell Telephone Laboratories in New York City. In Fig. 2 the transmitter, line, and receiver of the reference system are

shown on the three racks at the right. The calibration apparatus, consisting of an oscillator, thermophone, vacuum tube voltmeter, and volume indicator are shown on the other three racks. A schematic diagram of the master reference system is shown in Fig. 3.

The reference transmitter consists of a condenser transmitter and associated four-stage amplifier. The condenser transmitter is simple and rugged in construction. It has been available for work of this nature for several years during which time considerable experience has been obtained with it. In this system the condenser transmitter is held in an adjustable mounting and is equipped with a guard by means of which the speaker can keep his lips at a fixed distance from the diaphragm. This guard consists of a wire ring 4.7 cm. in diameter, held parallel to and at a distance of 4.1 cm. from the diaphragm of the transmitter by three wire supports. A volume indicator with meter visible to the speaker enables him to maintain an approximately constant talking intensity. In the condenser transmitter,⁵ shown in Fig. 4 and in cross-section in Fig. 5, a thin highly stretched duralumin diaphragm is mounted close and parallel to a steel plate grooved and perforated for air damping. This diaphragm and plate form the electrodes of a condenser polarized by a battery through a high resistance. Sound vibrations impinging on the diaphragm actuate it and produce variations in the

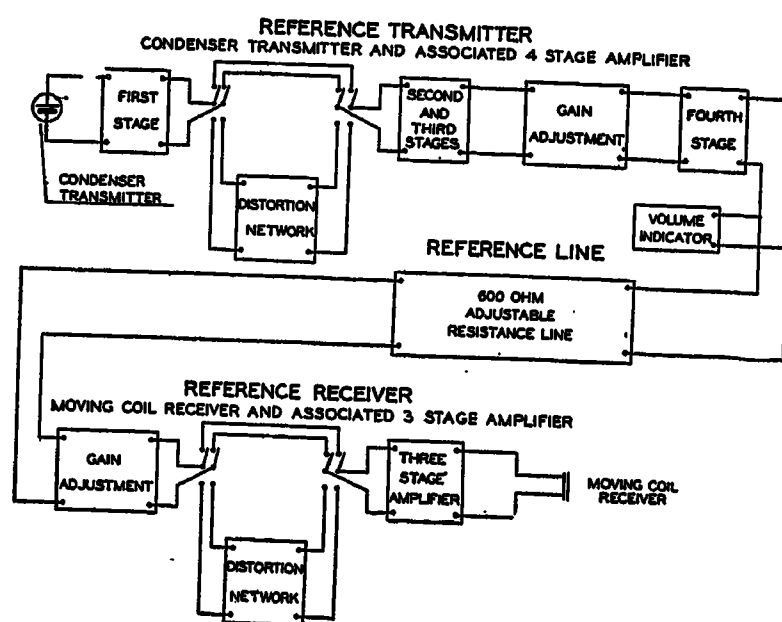


FIG. 3—SCHEMATIC DIAGRAM OF MASTER REFERENCE SYSTEM

capacity of this instrument. The resulting alternating potentials, faithfully representing the sound pressure waves, are amplified by the associated amplifier. Between the first and second stages of this amplifier, provision has been made for the introduction of distortion networks to simulate the distortion of any transmitting system. Between the last two stages are attenuating networks permitting adjustment of the relation between transmitter input and transmitter output over a range of 22 db. in steps of 0.1 db. The output impedance of the amplifier is 600 ohms with negligible phase angle.

The reference line consists of a series of balanced

resistance networks. This line has a characteristic impedance of 600 ohms matching the output impedance of the reference transmitter and the input impedance of the reference receiver, thereby eliminating any reflection effects at these junctions. By means of suitable controls the attenuation may be varied over a range of 101 db. in steps of 0.2 db.

The reference receiver consists of a moving coil receiver and associated three-stage amplifier. Means are provided for adjusting the relation between the

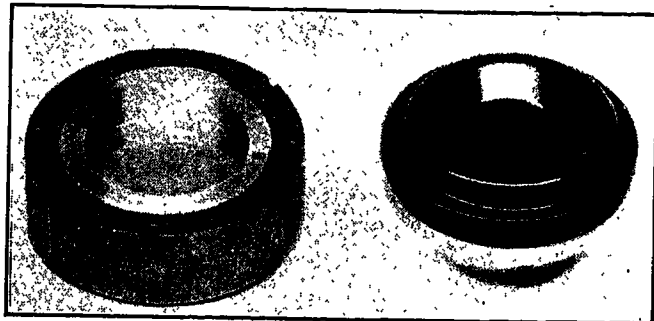


FIG. 4—CONDENSER TRANSMITTER AND MOVING COIL RECEIVER

input to the receiver and its output over a range of 22 db. in steps of 0.1 db. As in the case of the reference transmitter, provision has been made for the introduction of distortion networks to simulate the distortion of any receiving system. In the moving coil receiver⁶ shown in Fig. 4. and in cross-section in Fig. 7, a coil of aluminum ribbon, by vibrating relatively to a fixed permanent magnet, actuates a clamped, unstretched, thin duralumin diaphragm to which it is attached. Air damping in this receiver is secured by an arrangement somewhat similar to that employed in the condenser

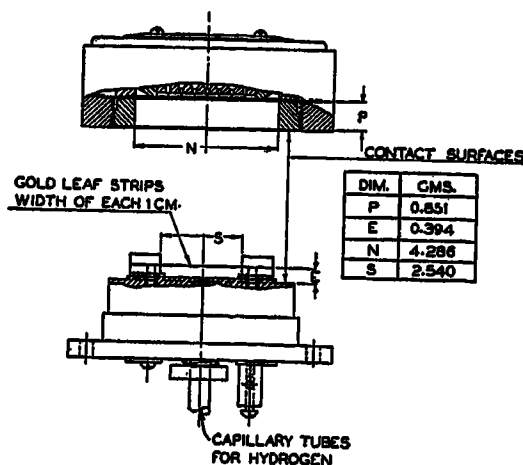


FIG. 5—SCHEMATIC DRAWING OF CONDENSER TRANSMITTER AND THERMOPHONE

transmitter. The structure is simple, rugged, and from the standpoint of freedom from distortion, its performance is comparable to that of the condenser transmitter. The central surface of the diaphragm is protected by a meshed wire screen instead of by the more usual type of receiver cap. This construction avoids resonance effects which would otherwise occur in the confined air space between diaphragm and cap. The contour of the ear piece, resembling that of the familiar telephone receiver, permits the listener to readily center the receiver on his ear.

In order that an individual part of any telephone circuit may be compared with the corresponding element of the master reference system, the system is arranged so that the reference transmitter, reference line, or reference receiver, may be replaced by the corresponding part to be rated.

CALIBRATION OF MASTER REFERENCE SYSTEM

To specify adequately the performance of the master reference system, in terms of definite physical quantities, apparatus is associated with the system for making electroacoustic calibrations of the reference transmitter and reference receiver, and electrical calibrations of the circuits. In general, the method employed in these calibrations is to adjust the setting of an attenuator to obtain a deflection on the galvanometer of a vacuum tube voltmeter, equal to the deflection produced when measuring the output of the element under calibration.

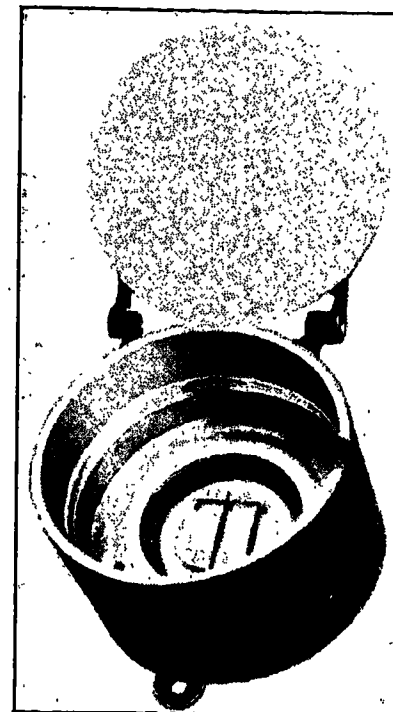


FIG. 6—THERMOPHONE IN CHAMBER FOR CALIBRATING TRANSMITTER

This avoids the necessity for an absolute calibration of the measuring device.

The source of alternating currents, used for calibrating purposes, is an oscillator, capable of producing currents with a harmonic output usually less than 3 per cent of the fundamental.

The measuring equipment used for making the above calibrations consists of a two-stage vacuum tube voltmeter in conjunction with a tuned circuit connected across its input. By means of this tuned circuit, harmonics of the fundamental frequency to be measured are attenuated by at least 20 db.

The calibration of the condenser transmitter is made with a thermophone, the gold leaf thermal elements being shown in Fig. 6. In Fig. 5 is shown a cross-section of a condenser transmitter and a thermophone. Petrolatum is used to form a seal between the instrument and the thermophone block. The air in this small enclosed chamber, formed by the walls and dia-

phram of the condenser transmitter and the thermophone block, is replaced by hydrogen. Since the velocity of sound in hydrogen is approximately 4 times that in air, the frequency range over which measurements may be made before standing wave effects are experienced is extended by the use of this gas. In addition, the efficiency of the thermophone is increased, the constant of diffusivity for hydrogen being greater than that for air. Both alternating and direct currents are passed through the gold leaf thermal elements, the direct current being sufficiently large to make negligible the double-frequency effect resulting when alternating current is supplied to the thermophone. The alternating current passing through the thermal-elements (gold leaf being selected because of its low heat capacity) causes variations in their temperature. Periodic expansions and contractions of the surrounding gas, resulting from the varying heat transfer occasioned by the periodic temperature changes of the thermal

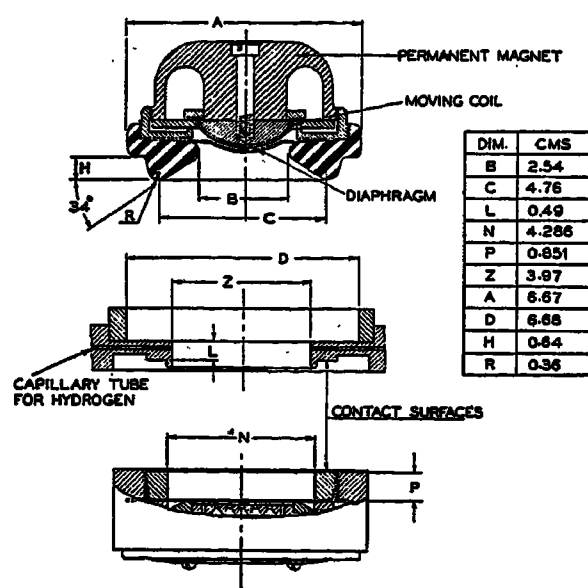


FIG. 7—SCHEMATIC DRAWING OF MOVING COIL RECEIVER, COUPLER, AND CONDENSER TRANSMITTER

elements, constitute sound waves of precisely determinable pressure. These sound waves actuate the transmitter and the ratio of the voltage output to the sound pressure gives the transmitter calibration. The process involved is as follows: Referring to Fig. 8.

E_T = Voltage generated by condenser transmitter per bar (one dyne/cm.²).

I_1 = Alternating current through thermophone and attenuator.

P = Pressure developed by thermophone per volt alternating current across it.

V_{VM} = Voltage across voltmeter.

A = Ratio of voltage delivered to 600-ohm load by the transmitter amplifier to voltage impressed in series with condenser transmitter.

V_o = Voltage across attenuator input.

R_1 = Input impedance of attenuator.

R = Thermophone resistance.

N = Attenuator setting in db.

T_P = Thermophone.

$C T$ = Condenser transmitter.

With the switches in Fig. 8 in position "A," the a-c. input to the thermophone and the amplifier gain are adjusted to obtain a convenient voltmeter deflection (V_{VM}). Then:

$$V_{VM} = I_1 R P E_T A$$

Operating the switches to position "B" and manipulating the attenuator to attain the same voltmeter deflection as before we obtain

$$V_{VM} = V_o A \times 10^{(-0.05N)} = I_1 R_1 A \times 10^{(-0.05N)}$$

Then:

$$E_T = \frac{R_1 \times 10^{(-0.05N)}}{R P}$$

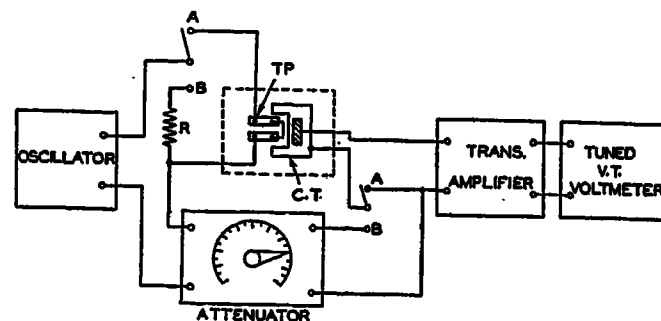


FIG. 8—CIRCUIT FOR CALIBRATING CONDENSER TRANSMITTER

The moving coil receivers are also calibrated in a sealed chamber in an atmosphere of hydrogen by an arrangement shown in cross-section in Fig. 7. A condenser transmitter, calibrated in the above manner, is actuated by the sound output of the receiver under test driven by the oscillator. The process involved is as follows: Referring to Fig. 9,

V_{VM} = Voltage across voltmeter.

V_o = Voltage across attenuator input.

V_R = Voltage across receiver terminals

$$= \frac{V_o R_R}{R_R + R_f} \times 10^{(-0.05N_a)}$$

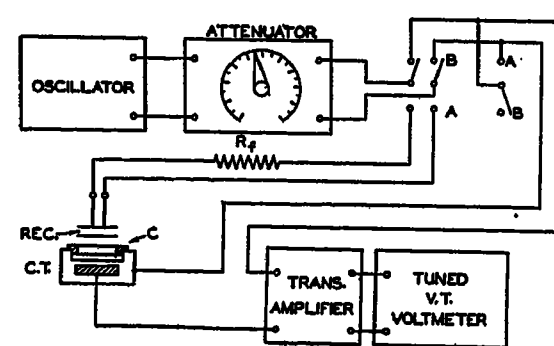


FIG. 9—CIRCUIT FOR CALIBRATING RECEIVER

R_R = Impedance of receiver plus cord.

R_f = Fixed resistance.

P_R = Pressure developed by receiver per volt across receiver terminals.

E_T = Voltage developed by condenser transmitter per bar (one dyne/cm.²).

A = Ratio of voltage delivered to 600-ohm load by the transmitter amplifier to voltage impressed in series with condenser transmitter.

N_a = Attenuator reading with switches on "A."

N_b = Attenuator reading with switches on "B."

C = Coupler (Fig. 7).

CT = Condenser transmitter.

With the switches indicated in Fig. 9 in position "A" the attenuator is adjusted to position N_a to produce a convenient deflection on the voltmeter (V_{VM}).

$$V_{VM} = V_o \frac{R_R}{R_R + R_f} P_R E_T A \times 10^{(-0.05N_a)}$$

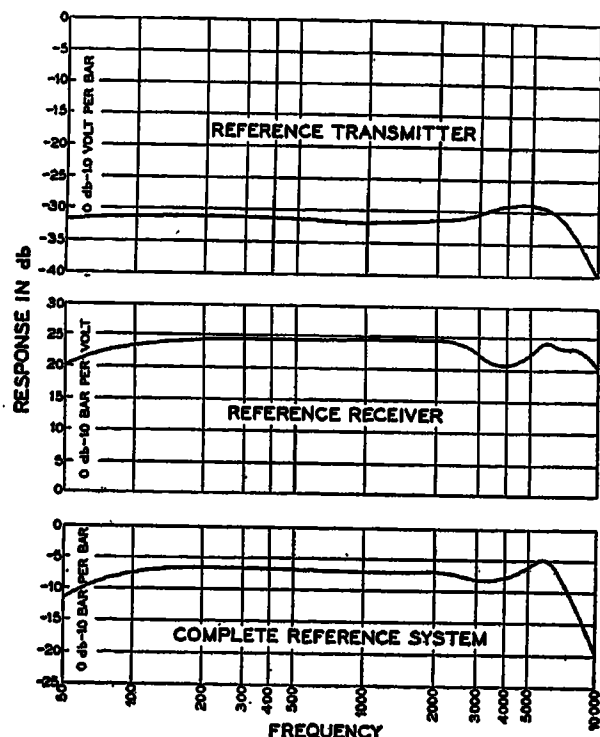


FIG. 10—RESPONSE CHARACTERISTICS OF REFERENCE TRANSMITTER, REFERENCE RECEIVER, AND COMPLETE REFERENCE SYSTEM WITH 0 db. IN THE LINE

Operating the switches to position "B" and adjusting the attenuator to some position N_b to reproduce the above voltmeter deflection V_{VM} we obtain:

$$V_{VM} = V_o A \times 10^{(-0.05N_b)}$$

Then:

$$P_R = \frac{(R_R + R_f) \times 10^{0.05(N_a - N_b)}}{R_R E_T}$$

The calibrations of the purely electrical elements of the circuit are made by measurements of input, output, and impedance.

Fig. 10 shows, for particular amplifier adjustments which are discussed below, the frequency response characteristics of the reference transmitter, reference receiver, and the complete reference system with 0 db. in the line. The characteristic of the reference transmitter and also of the reference receiver, in each instance, is that of the instrument and associated amplifier combined. However, as the frequency response of each of the amplifiers is uniform within 2 db., from about 50 to 10,000 cycles per second, the curves shown are essentially the calibrations of the instruments determined as described above. The primary purpose of these characteristics is to show the performance of these elements for definitely specified physical conditions. Consequently, no corrections are

included in these curves for the effect on the sound field of the speaker when talking into the condenser transmitter. Neither have corrections been applied for the effect of leakage between the listener's ear and the earpiece of the receiver nor for the difference between the volume enclosed in the sealed chamber when making the calibration as compared with the volume enclosed in the ear canal when the receiver is held to the ear. The reference line, consisting of balanced resistance networks, has a uniform frequency response characteristic. The characteristic of the complete system, therefore, except as its level is affected by the attenuation in the reference line, is that of the reference transmitter and reference receiver combined, there being no reflection effects at the junctions of the reference line with either the reference transmitter or receiver.

Fig. 11 shows the effect of introducing distortion networks in both the reference transmitter and reference receiver. The distortion network introduced in the reference transmitter simulates the distortion in the transmitter, station set, and cord circuit, of the standard cable reference system. Similarly, the distortion network introduced in the reference receiver simulates the distortion of the receiver, station set, and cord circuit, of the standard cable reference system. These two networks are designated, respectively, Transmitter Distortion Network No. 1 and Receiver

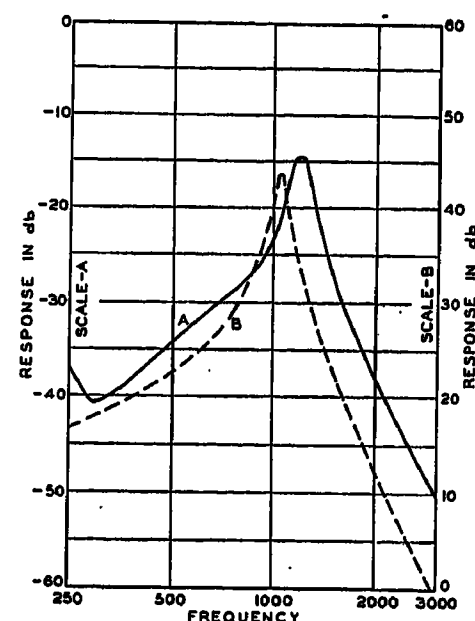


FIG. 11—RESPONSE CHARACTERISTICS OF REFERENCE TRANSMITTER AND RECEIVER WITH DISTORTION NETWORKS
A = REFERENCE TRANSMITTER—0 db.—1.0 VOLT PER BAR
B = REFERENCE RECEIVER—0 db.—1.0 BAR PER VOLT

Distortion Network No. 1. The distortion of any transmitter, receiver, or station set may be similarly simulated by the design and introduction in the master reference system of a proper network. The advantage of such a procedure will be evident to those familiar with the difficulties of making voice volume balances between instruments of widely different frequency characteristics. The volume efficiency of any instrument can also be reproduced by adjustment of the controls in the amplifiers of the reference transmitter or receiver as the case may be. The results of voice

volume balances made with the distorted reference system can be referred to the undistorted master reference system by applying a correction for the volume effect of the distortion network in the master reference system, this effect being determined independently as a rating of the distortion network.

Experience has shown that amplifiers properly designed and constructed remain essentially constant with time. Such changes in gain as may occur because of replacement of vacuum tubes or other apparatus may be readily compensated for by adjustments of potentiometers provided for this purpose. Condenser transmitters are affected to some extent by variations in temperature and barometric pressure. The magnitude of variation at any frequency between 50 and 10,000 cycles per second from these causes may be as much as 2.5 db., although under normal operating conditions such as those experienced in buildings in this climate, the variation is usually not more than 1 db. Since changes of this character are gradual in nature, their magnitude can be readily determined by a thermophone calibration. Corrections for any change in sensitivity of the instrument may then be made by adjustment of the controls in the amplifier associated with the condenser transmitter to maintain the proper gain in the reference transmitter. Similarly, any variations in the response of the moving coil receiver may be compensated for by adjustment of the gain controls in the amplifier associated with this receiver. The magnitude of the variations, at any frequency between 50 and 10,000 cycles per second, in the moving coil receiver may be as much as 3 db., although usually variations of less than 1.5 db. are observed. The calibration of the condenser transmitters, and indirectly of the moving coil receivers, is dependent upon the gold leaf thermophone, whose pressure characteristic is computed from physical measurements. Results obtained with thermophones can be held within about 0.5 db. of the average obtained by using a group.

COMPARISON OF MASTER REFERENCE SYSTEM AND STANDARD CABLE REFERENCE SYSTEM

Since the master reference system is to replace the standard cable reference system for volume ratings, the two systems have been compared by means of voice volume balances so that data obtained in the future may be directly comparable in this respect with those obtained in the past. The respective elements of the two systems, as well as the systems as a whole, have been compared. The station set and cord circuit at the sending end of the standard cable system are taken as comprising the transmitting element of that system and, likewise, the corresponding apparatus at the listening end as the receiving element. In these measurements the reflection gain at the junction of the standard cable line and the output terminals of the transmitting element of the standard cable reference system has been taken as part of the transmitting efficiency of that element. Similarly, the reflection

gain at the junction of the standard cable line and the input terminals of the receiving element of the standard cable reference system has been taken as part of the receiving efficiency of this element.

In the voice calibration of the master reference system to determine the adjustments which make this system equivalent on a volume basis to the standard cable reference system, eight series of voice tests were made. The purpose of the first five series of these tests was to determine the adjustments which make the master reference system with transmitter distortion network No. 1 and receiver distortion network No. 1 inserted in their respective elements, equivalent on a volume basis to the standard cable reference system. The purpose of the sixth and seventh series of tests was to determine the volume effects of the insertion of these distortion networks in the reference transmitter and receiver. The eighth series of tests was a direct comparison of the master system without distortion networks and the standard cable system, and so serves as an overall check on the determinations of the preceding tests.

In the first series of tests a comparison was made of the reference receiver with its distortion network and the receiving element of the standard cable system by interchanging the two in the standard cable system, with 24 miles of artificial cable in the line. The receiving element of the master system was adjusted so that its sound output was judged to be equal for this condition to that of the receiving element of the standard cable system. In the second series of tests a similar comparison was made of the reference transmitter with its distortion network and the transmitting element of the standard cable reference system. These transmitting elements were connected in turn to a 24-mile standard cable line terminated by the reference receiver with its distortion network, the receiver being adjusted in accordance with the results of the first series of tests. In the third and fourth series of tests the master reference system with the distortion networks in both the transmitter and receiver was compared with the standard cable reference system, the line of the master system serving as the adjustable element. These two series of tests were similar except that 24 miles of standard cable were used in one series of tests and 14 miles of standard cable in the other. The adjustments for the reference transmitter and reference receiver in these tests were those determined from the first and second series. From the results obtained in the third and fourth series of tests, the magnitudes were determined of the reflection gain at the junction of the standard cable line with either the reference transmitter or the reference receiver, and of the volume equivalent of 1 mile of standard cable in terms of db. The reference transmitter and reference receiver, each with its distortion network, were then readjusted in accordance with these data. The fifth series of tests served as a check on the results of the previous four series. In this

fifth series, the master reference system with transmitter and receiver distortion networks and 24 db. in the line was compared with the standard cable reference system with 24 miles of standard cable in its line.

In the sixth series of tests the adjustment of the reference receiver without distortion was determined to make it equivalent on a volume basis to the reference receiver with distortion. The reference transmitter with distortion and the reference line with 24 db. formed the rest of the system during these comparisons. In the seventh series of tests the sound output of the master reference system without distortion was compared to the sound output of this same system with distortion networks in the reference transmitter and reference receiver, the reference transmitter being adjusted to obtain a balance. During these tests 24 db. was kept in the reference line. The final series of tests, serving as a check on all of the above determinations, consisted of a comparison between the master reference system without distortion and the standard cable reference system, the line of the master system being adjusted in making this comparison.

In making voice tests to determine the above settings, the speaker, whose position with respect to the transmitters was kept constant, called standard testing sentences in a conversational tone. A given intensity of calling was maintained by watching the deflections on a volume indicator connected across the output of the transmitting element. An observer, located in a quiet room removed from the systems or instruments under test, determined when the two systems under comparison gave output sounds of equal loudness. Each testing team, consisting of a speaker and observer, made 12 balances. In order to attain a suitable precision in the final results of these tests, a large number of testing teams was used, the number being largest for the tests where the difference in the quality of the output sounds of the two systems under comparison was greatest. For example, for the first series of tests, six teams were used, for the fifth 25 teams, and for the eighth series, where the master reference system without distortion was compared with the standard cable system, balances were made with 37 teams. In all, over 2000 individual balances were made. The standard deviation of the determination for each of the first five series is of the order of 0.5 db. and for each of the last three series about 1 db.

The response characteristics of the transmitter and receiver elements of the master reference system, when adjusted on the basis of the results of the voice tests, to be equivalent on a volume or loudness basis to the corresponding parts of the standard cable reference system, are shown in Fig. 10. The mean values weighted from the standpoint of importance for volume are 0.027 volt per bar for the reference transmitter, 16 bars per volt for the reference receiver, and 0.43 bar per bar for the complete master reference system with 0 db. in the reference line. Further consideration is being

given to the values of these response characteristics of the reference transmitter and receiver to be adopted as standards.

The response characteristics of the reference transmitter with transmitter distortion network No. 1 and of the reference receiver with receiver distortion network No. 1, when these elements are adjusted on the basis of the above voice tests to be equivalent on a volume or loudness basis to the corresponding parts of the standard cable reference system, are shown in Fig. 11.

APPLICATION OF THE SYSTEM

The results of articulation tests over the master reference system when adjusted for optimum volume are practically equivalent to those obtained in direct air transmission in a quiet room. This system and replicas of it, are particularly adapted for use in making articulation studies, since they provide an approximately ideal system with which the loudness of the output sounds can be varied distortionlessly over a wide range and in which distortion networks of various types and controlled amounts of noise can be introduced. In this way the effects on articulation of various kinds of physical performance of a telephone circuit can be investigated.

The master reference system itself will be used chiefly for the important work of rating working standard systems and instruments. These working standards can be simpler than the master system and can be provided in any number required to handle the rating of commercial circuits and apparatus.

The working standard may be of several forms. It can be similar to the master reference system, simplified in its detailed construction but capable of calibration by the means employed for calibrating the master reference system. Such a system would probably find employment in laboratories and factories where the volume of testing is sufficient to justify the use of such apparatus. Another form may include electrostatic or electrodynamic instruments which are not capable of being measured by the calibration equipment of the master reference system. A third form which the working standard may take is that involving the use of transmitters, receivers, and station sets such as have been used in the standard cable reference system. These latter types of working standards can be calibrated by volume comparisons with the master system or with the first type of working standard. They will find their chief field of usefulness at such points as shops for the repair and recovery of station apparatus, where the volume of work is not sufficient to justify the expense involved in maintaining more elaborate working standards.

EUROPEAN MASTER REFERENCE SYSTEM

In Europe the recommendation of technical standards for telephony is a function of the Comité Consultatif International des Communications Téléphoniques à Grande Distance (C. C. I.), which is composed of repre-

representatives of the various European telephone administrations. In 1926, at the invitation of the C. C. I., representatives of the Bell System met in London with a committee appointed by the C. C. I. to consider the adoption of a transmission reference system. This committee recommended that the C. C. I. adopt as their master reference system a system essentially the same as the one described in this paper, and that such a system, which would be a replica of one in New York, be installed in Paris in the laboratory of the C. C. I. and be known as the European Master Reference System. This recommendation was adopted by the C. C. I.

Subsequently, some improvements were made in the system, and two duplicate systems, each with its associated calibrating apparatus, have been constructed. One of these is now in the Bell Telephone Laboratories in New York and the other in the laboratory of the C. C. I. in Paris. The C. C. I. further recommended that primary and working standard systems, used in the telephone administrations adhering to the C. C. I., be calibrated in terms of the Master Reference System. The establishment of these two master systems insures the use of a common base line for the expression of transmission standards, and for the ratings of the transmission performance of telephone circuits in the two continents where the telephone system has had its greatest development.

List of References

1. "Speech and Hearing" by H. Fletcher, D. Van Nostrand Co.
2. "Decibel" (db) is the name for the transmission unit which has superseded the "mile of standard cable." W. H. Martin, *Bell System Tech. Jl.*, January, 1929, and A. I. E. E. *Jl.*, Vol. 48, March, 1929, p. 223.
3. A discussion of a preliminary model of this system was given in "A Telephone Transmission Reference System" by L. J. Sivian, *Electrical Communication*, October, 1924.
4. The theory of the thermophone as a precision source of sound is outlined in papers by H. D. Arnold and I. B. Crandall,

Physical Rev., July, 1917, and by E. C. Wentz in the *Physical Rev.*, April, 1922.

5. The theory and operation of this transmitter are discussed in papers by I. B. Crandall, *Physical Rev.*, June, 1918, and E. C. Wentz, *Physical Rev.*, July, 1917, and *Physical Rev.*, May, 1922.

6. This instrument, which is similar in many respects to one described by E. C. Wentz and A. L. Thuras in the *Bell System Tech. Jl.*, January, 1928, will be discussed in a future paper by the same authors.

Discussion

F. A. Wolff: The reference standard for telephone transmission described in this paper and the apparatus and method that have been developed in connection therewith will in my opinion stand for many years to come.

In the first place, the apparatus and method meet the prime requirement of standards of measurement in that they give us something that is reproducible. In the second place, they furnish a practically distortion-free basis of reference. That eliminates much difficulty. Through the use of the supplementary distortion networks we are nevertheless able to make ready comparisons between actual telephone transmission of a distorted character and the reference network.

The use of the distortion network is exactly similar to the use of color filters in comparing incandescent lamps differing in the quality of the light which they emit. In general, wherever there is a difference of quality, there is difficulty in making comparisons, because human judgment must enter to such a large extent. Eyes differ, so do ears. That makes it necessary in comparing incandescent lamps of one color with those of another color or those of one efficiency with those of another efficiency, to use color filters. The factor for making allowance for this difference in color is determined by making a very large number of observations by a very large number of individuals in order to refer the result to the average individual and the average eye. So with these distortion networks used by the authors.

I think the Bell System is also to be congratulated because of the development of this method. Its presentation is indicative of the enormous improvements that have been made in the quality of commercial long-distance telephone transmission. Until that quality, which is very high today, far exceeds what it is, I do not think it will be necessary to make a revision of the master reference system for telephone transmission. I am sure that will not be required for a long time.

Electrical Wave Analyzers for Power and Telephone Systems

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and

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Synopsis.—This paper describes two types of electrical analyzers which have been developed for the direct measurement of harmonic components of voltage and current on power and telephone systems. These devices are assembled mechanically in a form suitable for use either in the laboratory or in the field. Both instruments, which differ chiefly with respect to sensitivity and input circuit arrangement, employ multistage vacuum tube amplifiers and two duplicate interstage selective circuits.

The power circuit analyzer is designed to measure harmonic voltages in the frequency range from 75 to 3000 cycles and over a voltage range from 0.5 millivolt to 50 volts. The telephone circuit

analyzer operates over the same frequency range and measures harmonic currents as low as 0.05 microampere and voltages as small as 0.005 millivolt. Both analyzers are adapted to measure small harmonic voltages and currents in the presence of the fundamental component and other harmonics relatively large in magnitude.

A number of devices are described which have been adopted for eliminating various sources of error. The paper presents in detail the characteristics of both instruments with respect to selectivity, sensitivity, linearity, balance of input with respect to ground, generation of harmonics, and susceptibility to stray fields.

* * * * *

INTRODUCTION

THE solution of many problems in electrical engineering, involving currents and voltages of complicated wave shapes can be most practicably carried out by a study of the individual sinusoidal components into which these complicated waves may be resolved. This is particularly true in the case of problems dealing with the inductive coordination of power and telephone systems, since the induced noise in telephone circuits occurs largely at frequencies corresponding to the harmonic components in the current and voltage waves of neighboring power systems.

In recent years, many of the development and research problems in inductive coordination, with which the Bell System has been concerned, have required an accurate and comparatively rapid field method of analyzing complex waves. The analyzers which are described in this paper have been developed to meet the particular requirements of these studies.† The development of these instruments has proceeded in close association with the progress of the field work and modifications were made in the designs from time to time as necessitated by the requirements of the work. This has resulted in the production of two types of analyzers, one of which is particularly adapted for use with suitable instrument transformers and shunts on power circuits, and the other for use on telephone circuits. These have been termed for convenience the "power circuit analyzer" and the "telephone circuit analyzer."

These analyzers have been in active service in the field for some time and have permitted the obtaining of much valuable data as to coefficients of induction between power and telephone systems, the wave-shape of power machinery and systems, and analyses of

noise currents on telephone circuits. They are arranged in suitable form for use either in the laboratory or in the field and in some instances have been mounted in specially equipped testing trucks.

Aside from their use in this work on inductive coordination, it is felt that the instruments may have a field in other power and communication problems in which a knowledge of the magnitudes of harmonic voltages and currents is important or where measurements at single frequencies are desired in the presence of extraneous voltages and currents as large or larger than the single frequency it is desired to investigate.

The over-all accuracy of an instrument of this type depends upon the conditions surrounding its use. These include the magnitude of the component being measured as compared to the magnitudes of the fundamental and other harmonics present, the relative magnitudes of the voltage across the terminals of the instrument and the voltage between these terminals and ground, and the severity of stray fields from nearby power circuits. Under average conditions, the analyzers which are described in this paper should give results with an over-all accuracy of within ± 5 per cent of the quantities measured. By means of these instruments it is possible to make a complete analysis of a complex wave over the frequency range up to 3000 cycles in from 30 to 45 min., depending upon the number of harmonic components present. The working up of the results in terms of volts and amperes consists in multiplying together not more than three quantities. The obtaining of a complete harmonic analysis in terms of volts or amperes should not, therefore, require more than one man-hour. The apparatus is so arranged that practically simultaneous analyses may be made of a number of currents or voltages.

GENERAL

As stated above, two general types of analyzers have been developed, the first, being designed for use on power systems, while the second, a more sensitive

*American Telephone & Telegraph Co., New York, N. Y.

†References to a number of other harmonic analyzers on which information has been published in recent years are given in a brief bibliography attached to this paper.

Presented at Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

instrument, is intended primarily for measuring currents and voltages of the magnitudes commonly experienced on telephone systems.

The requirements of both types of analyzers with respect to selectivity and at the same time insensibility to commercial frequency variations are practically the same. Therefore, the same selective equipment, designed to give a response curve which is parabolic in

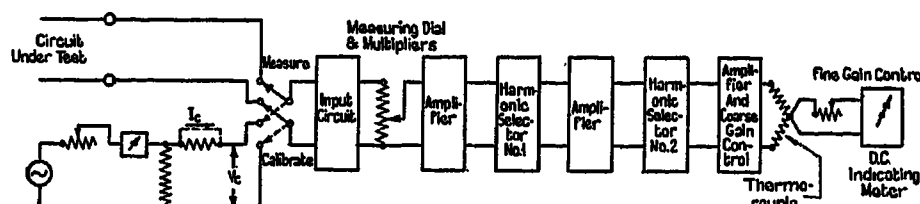


FIG. 1—SCHEMATIC DIAGRAM OF ANALYZER CIRCUIT

form, has been employed in both instruments. Other requirements which have been particularly considered in the development of the analyzers have to do with sensitivity, impedance of input circuits to be provided, insensibility to stray fields, and the limiting of harmonics generated within the instruments due to modulation effects. In both analyzers and in the telephone analyzer in particular, special consideration has been given to the matter of input circuit balance with respect to ground. This is in order that the accuracy of measurement may not be impaired when the voltage across the input circuit is small as compared to the voltage between the input terminals and ground, a condition which frequently obtains on telephone systems. The methods employed in meeting these various requirements and their effectiveness will be discussed in detail below.

Under ordinary conditions the telephone circuit analyzer may be operated satisfactorily on power systems. As will be brought out in the ensuing discussion, however, the power circuit instrument embodies somewhat greater refinement with respect to shielding from stray fields and the limiting of generated harmonics due to modulation. Although the sensitivities of the two instruments are necessarily different and while each instrument includes a number of special features, the general arrangements and methods of operation of the two analyzers are similar.

Electrical Circuit. Each analyzer consists essentially of a multistage vacuum tube amplifier equipped with suitable controls, a measuring dial and associated multipliers, a calibrating circuit, and a sensitive d-c. indicating meter operated by a thermocouple in the output circuit of the amplifier. Selectivity is afforded by means of duplicate tuned circuits inserted between stages of the amplifier. A schematic diagram indicating the general arrangement of the analyzer circuit is shown in Fig. 1.

To assist in visualizing its operation, the analyzer may be considered simply as a combination of a potentiometer and a sensitive selective a-c. voltmeter of infinite impedance, as indicated schematically in Fig. 2.

Let it be assumed that a voltage V_c applied to the input of the potentiometer, the sliding contact of which is set at a point C , results in a voltage V across the voltmeter. If the voltage V_c is replaced by a second voltage V_m of the same frequency and if with the potentiometer contact set at a point M , the same voltage V is reproduced across the voltmeter, then from the law of the potentiometer,

$$\frac{V_m}{V_c} = \frac{R_c}{R_m}$$

From this relation, it is evident that the potentiometer might be provided with a voltage scale, graduated in inverse proportion to the resistance, from which, using the voltmeter deflection as a reference, the ratio between two voltages as V_c and V_m might be determined directly. Similarly if the voltage V_c were a known voltage and the scale of the potentiometer were graduated in volts, the point C corresponding to the voltage V_c , the magnitude of an unknown voltage as V_m , might be read directly from the scale.

Referring again to the schematic diagram in Fig. 1, the actual operation of the analyzer circuit is as follows:

For calibration, the input circuit is connected to a source of known single-frequency voltage, V_c , or current I_c , the tuned circuits being adjusted for resonance at the calibrating frequency. The calibrated measuring dial is set to correspond to the magnitude of the calibrating current or voltage. The indicator of the output meter is then brought to a reference position by means of a set of controls which govern the gain of the amplifier. A definite relation is thereby established between the magnitude of the calibrating voltage or current, the indication of the measuring dial, and the deflection of the output meter. The input terminals are then connected to the circuit whose voltage or current wave is to be analyzed. For a complete analysis, the tuned circuits are adjusted progressively over the frequency range to be covered and as the meter responds at various

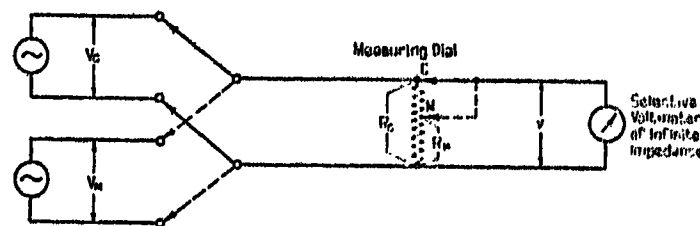


FIG. 2—EQUIVALENT CIRCUIT OF ANALYZER

frequencies, the tuned circuits are carefully adjusted to give a maximum deflection. The indicator of the meter is then returned to the original reference position by means of the measuring dial and its multipliers. The magnitude of each unknown harmonic is then determined from the product of the setting of the measuring dial, its multiplier, and a small correction factor for the frequency characteristic of the analyzer in case the frequency in question differs from the frequency at which the analyzer was calibrated. The frequencies of the measured harmonics are determined from the

settings of the adjustable condensers in the tuned circuits.

The particular circuit features of the power and telephone analyzers will be discussed in the following sections of the paper.

Mechanical Arrangement. For convenience in transporting and setting up the apparatus in the field, each type of analyzer has been assembled in two units, known as the "amplifier unit" and the "harmonic

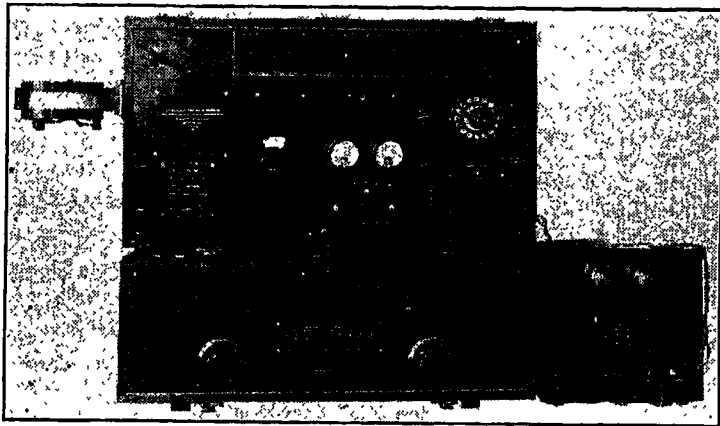


FIG. 3—POWER CIRCUIT ANALYZER AND CALIBRATING OSCILLATOR

selector unit" respectively. The selector units used with both the telephone and power circuit amplifiers are identical. An illustration of a completely assembled power analyzer, together with its calibrating oscillator, is shown in Fig. 3.

The lower unit in Fig. 3 is the harmonic selector, and includes all the equipment making up the two tuned circuits. This apparatus is assembled in a cabinet approximately 33 in. long, 12 in. high, and 11 in. deep, the whole weighing approximately 125 lb. The controls which appear on the panel of the selector unit are dials associated with the adjustable tuning condensers and keys for switching the various tuning inductances and fixed condenser units in and out of the circuit.

The amplifier unit as indicated in Fig. 3, is designed to be mounted directly on top of the harmonic selector. It is assembled in a cabinet of the same length and depth as the selector unit, but is approximately 19 in. high. The amplifier unit weighs approximately 200 lb. The controls which are provided on the panel of the amplifier unit include the measuring dial, a number of keys governing the various measuring circuits used, and miscellaneous equipment incidental to the operation of the amplifier. An ammeter for reading filament current is provided together with a voltmeter which, in conjunction with a number of push button type keys, is used for reading the voltages of the "B" and "C" batteries. The two dials mounted on the upper right-hand corner of the panel provide fine and coarse amplification controls respectively. The vacuum tubes extend outside the front of the panel and are covered by copper mesh which protects the tubes from mechanical injury and also acts as a shield against stray electrostatic fields.

The indicating meter used is of the edgewise type, giving a full-scale deflection on approximately 200

microamperes, and is ordinarily suspended from the left side of the amplifier unit.

The interconnections between the amplifier and selector units are provided with an electrostatic shield as indicated in Fig. 3.

In addition to the equipment outlined above, the analyzer requires an "A" battery of approximately 24 volts, suitable for supplying a current of one ampere, together with a "B" battery of 130 volts from which a current of approximately 40 milliamperes may be supplied.

HARMONIC SELECTOR

A wave analyzer for general use on power and telephone systems must meet two important requirements with respect to selectivity:

1. It must be sufficiently selective to permit the measurement of small harmonics in the presence of relatively large components at neighboring frequencies.
2. The shape of its response curve in the immediate neighborhood of the tuned frequency must be such as to permit small variations in the frequency of the component being measured without resulting in large variations in the magnitude of the analyzer reading.

Two independent tuned circuits operating in tandem,

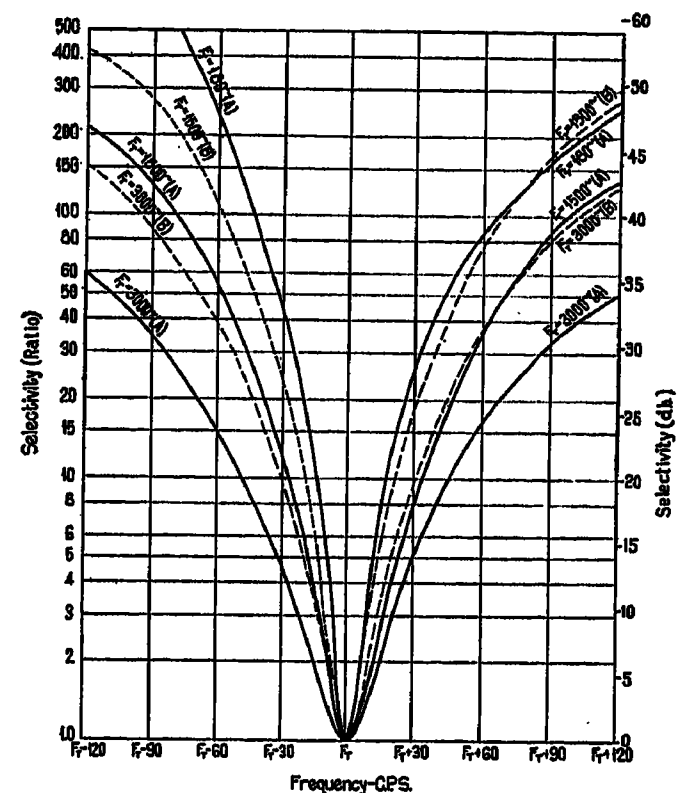


FIG. 4—SELECTIVITY OF TWO SECTIONS OF HARMONIC SELECTOR IN TANDEM

$$\text{Selectivity} = \frac{\text{Response at Tuned Frequency } (F_T)}{\text{Response at Extraneous Frequency}}$$

as employed in the analyzers which are described in this paper, seem particularly adapted to these requirements. The effect of the two circuits in tandem is to discriminate against extraneous harmonic components close to the tuned frequency in proportion to the square of the differences between their frequencies and that to which the circuits are tuned. The response curve obtained with such an arrangement is, therefore, approximately parabolic in form, being relatively flat in the immediate neighborhood of the tuned frequency

and falling off extremely rapidly at frequencies substantially different from that at which the circuits are in resonance.

The maximum selectivity available with two tuned circuits of this type could not be used practicably on commercial systems on account of the errors which would result from small frequency variations. It has been found desirable, therefore, to provide padding resistances which may be switched in series with the resonant circuits to degrade the selectivity somewhat.

The *A* curves in Fig. 4 indicate the over-all degree of selectivity obtained with the padding resistances in series with the two resonant circuits, this being the arrangement commonly used. As may be seen from the 180-cycle *A* curve, it is possible to measure a 180-cycle harmonic in the presence of a 300-cycle component 50 times as great. Since the meter measures the r. m. s. sum of the desired and undesired components, the latter in this case will cause an error of only 2 per cent.

The effect of variations in frequency on the stability of the analyzer reading is indicated by the curves in Fig. 5. These curves are for the normal operating condition, that is, with the padding resistances in series with the tuned circuits. It should be borne in mind that the frequency changes on power systems

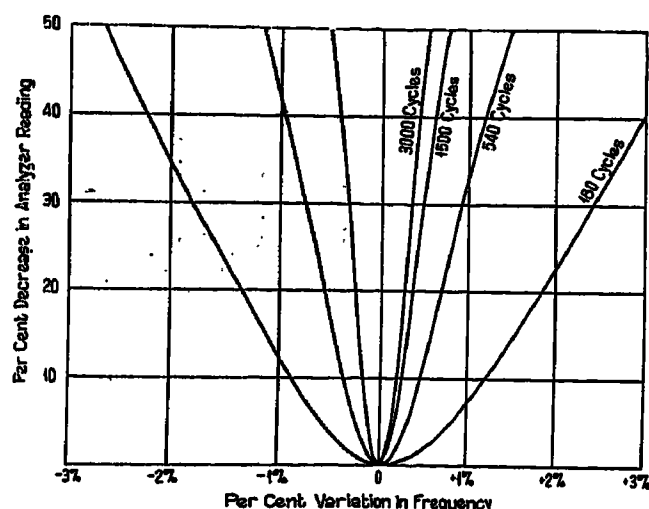


FIG. 5—STABILITY OF ANALYZER READINGS WITH FREQUENCY VARIATION

Two harmonic selector sections in tandem

referred to here take place comparatively slowly. In the time ordinarily required to make a given measurement, therefore, little trouble is experienced from frequency variations.

In cases in which a very high degree of selectivity is required, in the range from 540 to 3000 cycles, and in which the frequency stability of the generating source will permit, the padding resistances may be short-circuited. The degree of selectivity obtained under this condition is indicated in the *B* curves of Fig. 4.

A schematic circuit diagram of a single section of the harmonic selector unit is shown in Fig. 6. As is indicated in this figure each section consists essentially of a series resonant circuit consisting of a fixed inductance and an adjustable capacity. This resonant circuit is coupled to the plate filament circuit of the preceding

amplifying tube by a condenser of relatively low impedance ($4.5 \mu\text{f.}$) which is common to both circuits. The voltage across the inductance branch is utilized as the output of the tuned circuit and is impressed across the grid filament circuit of the following amplifying tube.

In the design of the harmonic selector it was found impracticable to employ a single tuning inductance over the entire frequency range from 50 to 3000 cycles. Such an arrangement would either require a broad and expensive range of adjustable capacities or, if relatively small capacities and large inductances were used, the large impedances of the capacity and inductance branches would render the circuit susceptible to the effects of leakage. Furthermore, variations in ampli-

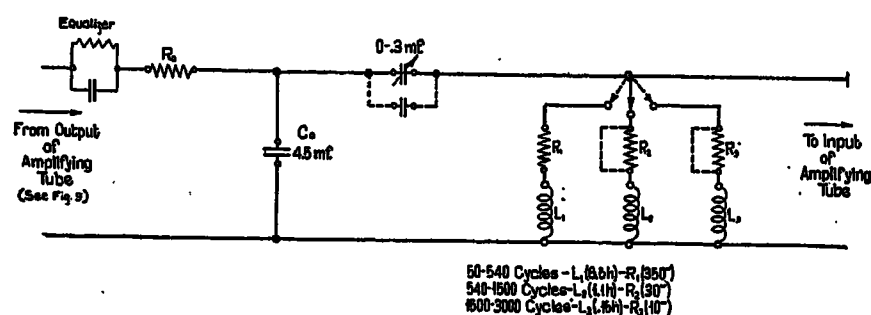


FIG. 6—SINGLE SECTION OF HARMONIC SELECTOR—SCHEMATIC

fication over the range of tuned frequencies would be excessive owing to variations in the losses in a single coil.

An arrangement which has proved practicable provides three tuning inductances of 8.5, 1.1, and 0.15 henrys, respectively, for covering the frequency range as indicated in Fig. 6. Frequencies from 100 to 3000 cycles are covered by adjustable condensers having capacities from 0.0001 to $0.3 \mu\text{f.}$ The selector is tuned for 50, 60, and 75 cycles by means of fixed condensers which may be connected in parallel with the adjustable units.

The harmonic selector is arranged to give an amplification-tuned-frequency characteristic which is relatively flat over the frequency range from 180 to 3000 cycles. The resistance R_0 , Fig. 6, is approximately equal to the impedance of the plate filament circuit of the tube, providing for maximum undistorted output power. Since the reactance of the coupling condenser C_0 is small as compared to the sum of R_0 , and the tube output impedance, the current I_0 for a given voltage across the grid filament circuit of the tube is practically independent of frequency. Similarly, since the reactance of the coupling condenser is generally (except at the lower ends of the tuning ranges) small compared to the effective resistance of the tuned circuit, the voltage impressed on the tuned circuit is

$$V_0 = \frac{I_0}{\omega (C_0) (10^{-6})}, \text{ approximately}$$

which is inversely proportional to frequency. If the effective resistance of the tuned circuit, R_e , were con-

stant the output voltage at any tuned frequency would, therefore, be

$$V_L = \frac{V_0 (\omega L)}{R_e} \text{ approximately}$$

$$= \frac{I_0 L}{R_e C_0 (10^{-6})} \text{ approximately}$$

and would be independent of the tuned frequency. Actually, of course, the effective resistance of the tuned circuit increases considerably with frequency and the above relation holds over a very limited range of tuned

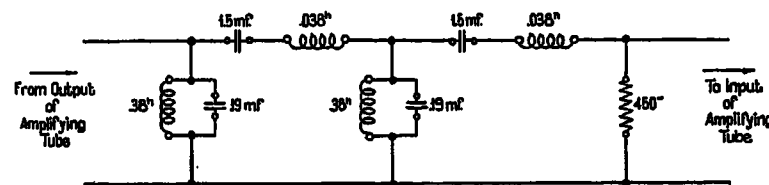


FIG. 7—FILTER FOR R. M. S. MEASUREMENTS—CIRCUIT DIAGRAM

frequencies only. The effect of the increasing effective resistance on the amplification-frequency characteristic of these analyzers is largely neutralized, however, by the insertion of an equalizing circuit consisting of a capacity and resistance in parallel connected in series with the resistance R_0 . The remaining effect is taken care of in curves furnished with the instruments in cases in which measured frequencies differ from those at which calibrations are made.

The differences in amplification in the frequency ranges covered by the three tuning inductances are taken care of by independent corrective resistance networks, associated with the resistance R_0 , in the three ranges.

In addition to the arrangements for measuring the fundamental and individual harmonics, an additional circuit is provided for measuring the r. m. s. sum of all harmonics between 180 and 3000 cycles. This device includes two sections of modified confluent band filter which may be substituted for the first tuned circuit of the harmonic selector and an equalizer section, for flattening the frequency characteristic in the measuring range, which is substituted for the second tuned circuit. The transmission-frequency characteristic of this arrangement is such as to cut off between 60 and 180 cycles and between 3000 and 5000 cycles, the curve in the range between these points being practically flat. A diagram of the circuit for r. m. s. measurements is shown in Fig. 7.

POWER CIRCUIT AMPLIFIER

In the design of a suitable amplifier unit for use with the harmonic selector in measurements on power systems the following requirements have been particularly considered:

1. Its input circuit including the measuring dial and multipliers must be linear with current and voltage over the range to be measured at any given frequency.

2. The input circuit must be sufficiently well balanced with respect to ground to permit the measurement of small voltages and currents with relatively large voltages existing between the input terminals and ground.

3. Harmonics generated within the instrument itself must be kept at a minimum and if possible should be less than those generated in instrument transformers commonly used on power systems.

4. Its accuracy must not be impaired by pick-up from such stray electromagnetic and electrostatic fields as are commonly experienced in the vicinity of power apparatus.

As stated above, the amplifier unit consists of a vacuum tube amplifier and its associated controls together with a measuring dial and a calibrating circuit. Three input circuits are provided for measuring power circuit voltages, currents, and small voltages across shunts, respectively. The impedances of these three circuits and the sensitivities available are as follows:

Quantity measured	Input impedance	Minimum measurable current or voltage
Voltage.....	10,000 ohms	0.05 volt
Current.....	0.2 ohm	2.5 milliamperes
Millivolts.....	1,000 ohms (Approx.)	0.5 millivolt

At fundamental frequencies the minimum measurable voltages and currents are ten times those given above.

The 10,000-ohm voltage circuit is intended for use across the secondaries of potential transformers or in other locations where the fundamental voltage does not exceed 110-150 volts. The 0.2-ohm current measuring circuit is designed particularly for use in the 5-ampere secondaries of current transformers. It is designed to carry continuously a current of 7.5 amperes. The

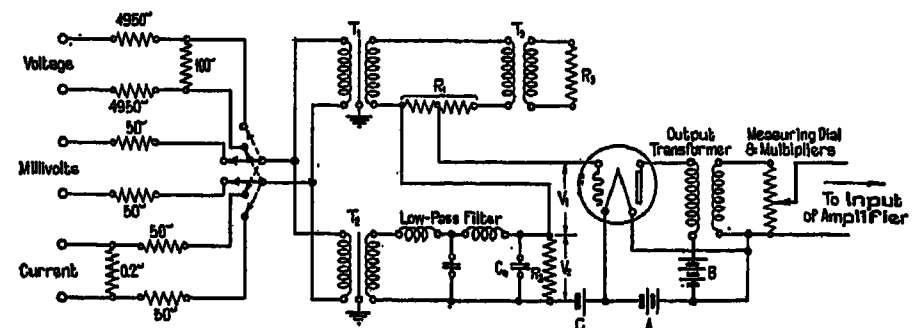


FIG. 8—POWER ANALYZER—INPUT CIRCUIT—SCHEMATIC

millivolts circuit may be used under a variety of conditions and is particularly intended for use with power system shunts. The constants of the three circuits are so arranged that their calibrations are made simultaneously by a single adjustment of the amplifier gain.

A schematic diagram indicating the general arrangement of the input circuits in the power amplifier is given in Fig. 8. These circuits are designed to measure harmonic components over a range of from 1 to 1000 times the current and voltage values given in the above table. Errors due to non-linearity in the input circuits

over this range do not exceed approximately ± 3 per cent at frequencies from 120 to 3000 cycles. Except at the extreme ends of the scale at frequencies below 180 cycles such errors do not exceed ± 1 per cent. Fundamental components of current and voltage can be read up to 7.5 amperes and 150 volts, respectively.

In order to avoid errors due to the effects of relatively large voltages to ground on the input terminals the input circuits are accurately balanced with respect to ground. Transformers whose primary windings are especially well balanced and which include interwinding electrostatic shields are employed between the line terminals and the measuring circuit. Similar precautions are taken to avoid unbalances and stray capacity effects in the wiring external to the transformers. As an example, the degree of balance attained in the input circuits of one particular instrument is indicated in the following table. These figures represent the apparent voltages across the circuit resulting from the effect of one volt between the input terminals and ground, the analyzer being adjusted to measure 60-cycle harmonics:

Frequency (c. p. s.)	Apparent voltage across measuring circuit per volt above ground	
	Current and millivolts circuit	Voltage circuit
180	0.000007	0.0007
540	0.000008	0.0008
1020	0.000013	0.0014
2100	0.000021	0.0022
3000	0.000024	0.0027

In order to avoid the generation of harmonics of appreciable magnitudes within the analyzer itself due to modulation effects it was found necessary to provide special devices for suppressing the fundamental component of the wave under analysis and for balancing out harmonics generated in the input transformers. A brief description of the operation of these features of the input circuit is as follows:

Referring to Fig. 8, it will be seen that two parallel input circuits are provided, one consisting of the transformers T_1 and T_3 and the resistance R_1 , the second consisting of the transformer T_2 , a low-pass filter, and the resistance R_2 . In the first branch, the complex voltage impressed across the primary of the transformer T_1 is reproduced in practically undistorted form across the resistance R_1 . In the second parallel branch, the harmonics in the complex wave are effectively suppressed by the low-pass filter, the voltage across the terminating resistance R_2 being of practically pure fundamental frequency. By a proper adjustment of the circuit constants, the voltage across R_2 may be made practically equal to an opposite in phase to the fundamental component of a portion of the complex voltage across R_1 . By impressing these two voltages in series across the grid circuit of a vacuum tube,

the fundamental component of the complex wave is effectively balanced out.

With the fundamental component eliminated ahead of the first amplifying tube there remain the harmonic components originally in the complex wave and those generated in the input transformers. These latter components, which result in errors in measurements of small harmonics, may be effectively reduced by means of a third transformer T_3 connected as indicated in Fig. 8. By a proper adjustment of the resistance R_3 across the secondary of the transformer T_3 the harmonic components of current in the resistance R_1 generated in the transformers T_1 and T_2 are effectively neutralized by equal and opposite components generated in T_3 . The voltage V_1 across a portion of R_1 , which is impressed across the input circuit of the tube is, therefore, practically free from generated harmonic components.

These means for controlling the generation of harmonics in the power analyzer have proved very effective. In one particular instrument the generated harmonics observed in the case of a 60-cycle fundamental voltage of 102 volts were as follows:

Fundamental voltage	Per cent generated harmonics						
	2nd	3rd	4th	5th	6th	7th	9th
102 volts.....	0.07	0.08	0.008	0.02	*	*	*

*Too small to measure—less than 0.01 per cent.

The power amplifier unit is specially shielded against stray electrostatic fields at all susceptible points with copper shielding. Similar shields of annealed iron are provided with all susceptible wound apparatus as a protection against stray electromagnetic fields. A large number of tests carried on in the field indicate that the analyzer is sufficiently well shielded for general use in the vicinity of power apparatus.

A circuit diagram of the amplifier which is used in conjunction with the input circuits described above is shown in Fig. 9. This portion of the circuit is identical in both the power circuit amplifier and the telephone circuit amplifier which is to be described below.

TELEPHONE CIRCUIT AMPLIFIER

The amplifier which has been designed for use with the harmonic selector on telephone systems differs from the power circuit amplifier chiefly in the matter of sensitivity and in the arrangement of its input circuits. Six vacuum tubes are used in the telephone circuit amplifier as in the case of the power circuit unit. In the former, however, added amplification is obtained by the utilization of the first tube as a voltage amplifier instead of as a blocking device as in the power circuit analyzer.

A schematic diagram of the input circuit of the telephone circuit amplifier is shown in Fig. 10. As is indicated in this diagram the input circuit is provided

Input circuit	Frequency	Apparent voltage across circuit
Current (6-ohm).....	3000	0.0000015
Current (6-ohm).....	540	0.00000035
Current (600-ohm).....	3000	0.000012
Current (600-ohm).....	540	0.000002
Voltage (120,000-ohm)....	3000	0.00029
Voltage (120,000-ohm)....	540	0.00002
Voltage (0.00025 μ f.)....	3000	0.0046
Voltage (0.00025 μ f.)....	540	0.0042
Power voltages.....	3000	0.025
Power voltages.....	540	0.001

As is indicated in the circuit diagram of Fig. 10, a high-pass filter consisting of a series condenser of 1.5 μ f. and a shunt inductance of 0.5 henry is included in the input circuit. This filter is effective on systems having a fundamental frequency of 60 cycles or less, in suppressing the fundamental component of the complex wave under analysis. The condenser may be connected on either side of the inductance in order that the filter may be used effectively either in series with a high impedance or in shunt with a low impedance as may be required by the particular measuring circuit employed. This device results in an average reduction in the fundamental of 13 decibels which is equivalent to approximately 80 per cent. The generation of harmonics in the analyzer due to modulation effects is, therefore, practically confined to the input transformers. The magnitude of the fundamental component, as compared to the amplitudes of the harmonics, is usually considerably less in the case of telephone circuits than on power systems. A somewhat larger degree of harmonic generation can be tolerated, therefore, in the case of the telephone circuit analyzer. The generated harmonics in one particular telephone circuit amplifier unit, expressed in per cent of the fundamental component are as follows:

Circuit	Fundamental component	Per cent generated harmonic			
		2nd	3rd	5th	7th
Current (600-ohm).....	0.001 ampere	0.28	0.27	0.049	0.006
Current (6-ohm).....	0.01 ampere	0.25	0.25	0.05	0.009
Voltage (120,000-ohm)....	10. volts	0.25	0.25	0.05	0.007

While the telephone circuit amplifier is not ordinarily exposed to stray fields of large magnitudes, the instrument has been shielded at susceptible points in much the same manner as the power analyzer. Tests in the laboratory and in the field indicate that, except under unusually severe conditions, the shielding is sufficient to permit the use of the analyzer in the vicinity of power apparatus.

CALIBRATING OSCILLATOR

As discussed above, a source of current or voltage of known frequency is required with the analyzers for calibration purposes. For use in cases in which one of the standard adjustable-frequency oscillators is not available a small portable vacuum tube oscillator has been developed.

The calibrating oscillator employs two tubes, the first functioning as an oscillator and the second as an amplifier as indicated in the circuit diagram shown in Fig. 11. The circuit is arranged to produce frequencies of 180, 540, 1500, or 3000 cycles. These permit calibration of the analyzers in each of the three frequency ranges covered by the harmonic selector and also provide suitable frequencies for checking the frequency characteristics at both ends of each range. The oscillator is designed to give a minimum output of 10 milliamperes in 150 ohms at each frequency. The wave-shape of the output at each frequency is such that the r. m. s. sum of all the harmonics is less than 5 per cent of the fundamental.

The equipment making up the oscillator is assembled in a cabinet approximately 13 in. long, 12 in. wide, and 7 in. deep, the complete unit weighing approximately

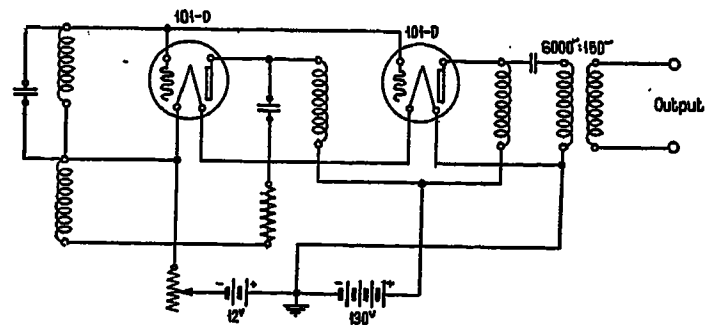


FIG. 11—CALIBRATING OSCILLATOR—CIRCUIT DIAGRAM

35 lb. One of the calibrating oscillators is included with the power circuit analyzer in the illustration shown in Fig. 3.

The current supplied by the oscillator to the calibrating network is controlled by a potentiometer located in the amplifier unit. The magnitude of this current is determined from the reading of a thermal milliammeter consisting of a thermocouple and the galvanometer provided with the amplifier unit.

Bibliography

The following list of references is by no means intended as a complete bibliography on the subject of harmonic analysis. It is merely to tabulate references to a number of noteworthy articles on the subject which have come to the attention of the authors.

1. "An Electrical Harmonic Analyzer," J. D. Cockroft, R. T. Coe, J. A. Tyacke, and M. Walker, *Jl. I. E. E.*, Vol. 63, Jan., 1925.
2. "Une Méthode Potentiométrique d'Analyse Harmonique des Ondes des Comants Alternatifs des Alternateurs," A. Blondel, *Rev. Gén. de l'Elec.*, Mar. 7, 1925.
3. "An Electrical Frequency Analyzer," R. L. Wegel and C. R. Moore, *Bell System Tech. Jl.*, Apr., 1924.
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5. "Analyzer for Complex Electric Waves," A. G. Landeen, *Bell System Tech. Jl.*, Apr., 1927.
6. *A Simple Harmonic Analyzer*, V. Bush, *Jl. A. I. E. E.*, Vol. 39, 1920, p. 903.
7. *An Electromechanical Device for Rapid Schedule Harmonic Analysis of Complex Waves*, F. S. Dellenbaugh, Jr., *TRANS. A. I. E. E.*, Vol. 40, 1921, pp. 451-478.

8. *Another Harmonic Analyzer*, F. S. Dellenbaugh, Jr., A. I. E. E. J., Jan. 1923, pp. 58-61.

9. "Harmonic Analyzer for Use on Power Circuits." Serial Report of the Inductive Coordination Committee, National Electric Light Association, Jan., 1928.

Special attention is called to an extensive bibliography on this subject appended to Professor Dellenbaugh's paper of 1921.

Other references are included in a bibliography published by the American Committee on Inductive Coordination in 1925.

Discussion

J. J. Smith: The principal lines along which efforts have been made in the past to develop such analyzers are: (1) By means of tuned circuits, similar to the analyzer described in this paper, where the frequency which it is desired to measure is tuned and the others are reduced by attenuation. (2) By use of the dynamometer principle where a known current of the frequency which it is desired to measure is introduced in one coil of the dynamometer and the wave to be analyzed is in the other coil. The first suggestion in the literature that I have been able to find of an analyzer of the first type is in a paper by Pupin entitled *Resonance Analysis of Alternating and Polyphase Currents*, A. I. E. E. TRANS., Vol. XI, 1894, p. 523.

An analyzer of the second type was suggested in an early paper by Dr. L. Duncan and later developed into a practical form which is described in the paper in reference 1 of the bibliography.

Although the fundamental principles were embodied in the above papers we had to await the development of the vacuum tube before the instruments could be developed to high sensitivity and high accuracy.

In addition to the development of the vacuum tube the proper balance and shielding of such apparatus has to be carefully considered, and the figures given by the authors on p. 1172 show that this has been well taken care of. I have used one of these analyzers for the last few years and experienced no difficulty due to extraneous fields when the apparatus is set up in the vicinity of the usual type of machines tested in the factory. On one occasion, however, when making measurements on a large reactor, trouble was experienced due to pick-up in the instrument (which was set quite close to the reactor). This pick-up, however, was easily detected since it was independent of the multiplier and dial readings. The remedy, of course, was to remove the instrument to some distance from the reactor.

The input circuit described in Fig. 8 of the paper, while allowing high accuracy for standard frequencies such as 25, 50, and 60 cycles, is not always very suitable for work in the factory where it may be desirable to make experiments over a range of intermediate frequencies. I would suggest that the authors give a table showing the probable error for the frequencies in between.

Our experience in using this meter confirms the statement that the analyzer described gives results within ± 5 per cent of the quantities measured, since we have made measurements on a machine and repeated them later under as nearly as possible the same set of conditions and the results agreed within the above order of accuracy.

It may be interesting to point out that with the sensitivity obtained with this analyzer we have gone down to the region where harmonics generated in other parts of our measuring equipment may be a source of error. For instance, in measuring on a high-voltage line it is necessary to use potential or current transformers. On account of the characteristics of the magnetization curve of iron the exciting currents of these transformers will contain harmonics which, although small, will affect the result if the wave which is being measured is very close to a sine wave.

J. O. Coleman: The authors of the paper on electrical wave analyzers deserve considerable credit for the development of the apparatus. I have had occasion in the past five years, in connection with the joint development and research of the N. E. L. A. and the Bell System, to use the analyzers for measurements under many varied conditions. Needless to say, there have been times when we have had considerable trouble in making the required measurements, and part of the time the difficulty was with the analyzer.

Mr. McCurdy mentioned the development since the first analyzer was constructed. I also used the first one. With it a fraction of an ampere in a wire 15 or 20 ft. away, under some conditions, would cause full-scale reading on the meter with nothing connected to the input terminals. With the improved models we have made analyses, in a power substation, over the top of 15 to 20 outgoing feeders with no serious disturbance from them. This, I think, speaks quite highly for the development of the shielding.

The analyzer in the paper appears to be quite a complicated piece of apparatus. One would think that with all the dials and the switches on it, considerable time would be required for measurements. In connection with some of our work, we have made upward of 2000 separate measurements a day.

Another consideration in speaking of balance is that there are two ways of considering ground as far as the analyzer is concerned. If you tie the analyzer shield to the earth, you have to face whatever potentials you are placing on the input coil. The other alternative is to tie the analyzer shield to whatever circuits you are measuring and thereby eliminate the large voltage across the input coil. The analyzer has been used satisfactorily, directly connected to a 2300-volt circuit with its batteries and operator completely isolated from the ground.

There is a number of by-products of anything. In some of the work we had occasion to measure the impedance of equipment at the harmonic frequency with the lower frequencies present. Some equipment may have different impedance at 300 cycles; for instance, when 60 cycles are present from the impedance it has when the 60 cycles are not present. In cases of this character the analyzer can be used strictly as a galvanometer and measurements obtained which would be otherwise very difficult.

L. J. Corbett: (communicated after adjournment) The authors have described the most recent type of mechanical analyzers of periodic e. m. f. and current waves, by which the strength of the components of each frequency may be measured with considerable accuracy,—while it remains constant. The modern developments in amplifiers are made use of in the measurement of very low values of some of the components. In discussing the paper, the writer has no wish to detract from the praise which is justly due to the engineers of the telephone industry and of the power industry whose efforts have produced such an accurate, usable, and strong instrument. Instead he wishes to supplement the paper by adding a word of caution regarding its use.

The waves which are most commonly analyzed by the use of such equipment are those which exist in power circuits, or which may be produced inductively in a second circuit not far removed from a power circuit. The waves in an ordinary power circuit are subject to fluctuations which primarily affect the voltage, and secondarily, the relative proportions of the various harmonics when electrical equipment containing iron magnetic circuits is involved. A third possibility is a slight change in fundamental frequency following load changes, which in turn alters to a far greater degree the frequencies of the higher harmonics. Again, resonance conditions in the power circuit may so favor certain frequencies that the slight change in fundamental frequency in itself changes the relative values of the various harmonics. Speed changes on a 60-cycle system may amount to 0.4 cycle high or low, the return to normal being rather slow and gradual. On the higher harmonics this will amount to several cycles, and from the

curves of Fig. 5 of the paper, the accuracy is low and a re-setting is necessary. In the re-setting, it is evident that conditions are not the same as when the earlier readings were taken, so the readings of the various harmonics taken consecutively are only roughly comparable. Only by simultaneous readings of several mechanical analyzers can dependable readings of a number of harmonics be obtained.

A mechanical analyzer tells nothing of the relative phases of the different harmonics so it does not tell the whole story. Important physical relations are thus slighted, which, if they were known, would give a clearer insight into electric wave phenomena.

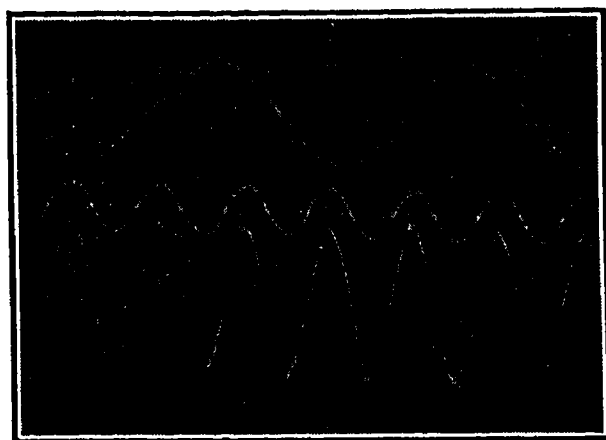


FIG. 1—RESIDUAL CURRENT ON LINE SERVING Y/Y BANK

It appears to the writer that more use can be made of the oscillograph, possibly in conjunction with the mechanical analyzer. The oscillograph in its present stage of development, is admittedly a rather coarse-reading instrument. However, it does show the relative phases of the lower harmonics quite obviously, and the relative phases of the higher harmonics by somewhat tedious methods of measurement and calculation.

The determination of residual current and voltages in three-phase power systems is the aim of many investigations in which analyzers of the type described in the paper are used. To illustrate some of the physical relations existing which can be shown by the oscillograph, the accompanying oscillograms are presented. At the substation at which the tests were made there were two



FIG. 2—RESIDUAL CURRENT ON LINE SERVING Y/Δ BANK

busses, on one of which all lines and transformer banks were first connected. One transmission line at a time was then served by the second bus through the bus paralleling switch. The residual current for each line was obtained from the current transformers of the paralleling switch and was recorded on the middle element of the oscillograph. Above is a 60-cycle timing wave from the station lighting circuit, and below is a constant 180-cycle reference wave obtained between the neutral of a Y-connected set of coils on the 110-volt side of the potential transformers of the first bus, and ground.

The substation at which the tests were made contained only Y-connected transformers with neutrals grounded and without deltas. In Fig. 1 herewith the middle element shows the residual current in a line from the substation serving a station at which a large Y-Y bank with grounded neutral is connected without a delta. In Fig. 2 the same element shows the residual current in a line to a station where the banks are connected grounded Y to delta. In Fig. 3 the line concerned was energized but disconnected at the other end, a combination of leakage and charging current being obtained.

There can also be shown the reversal of direction of flow of such currents due to system changes, as illustrated in a paper presented by the writer before the Pacific Coast Convention of the Institute at Spokane last year.¹ Because of these physical relations which are ignored by the analyzer, it appears that the use of such an instrument as the oscillograph in conjunction with it, would assist materially in many problems.

P. W. Blye: As pointed out by Mr. Smith in his discussion, the input circuits of the power analyzers are provided with fixed values of resistance (R_1 , Fig. 6 of paper) and capacity (C_0) to reduce generated harmonics to a particularly low level when the fundamental frequency is 25, 50, and 60 cycles. These three frequencies were selected as those most likely to be encountered in practise. There is no reason, however, why additional values of the resistance R_1 and the capacity C_0 might not be provided for use with other fundamental frequencies, if desirable.

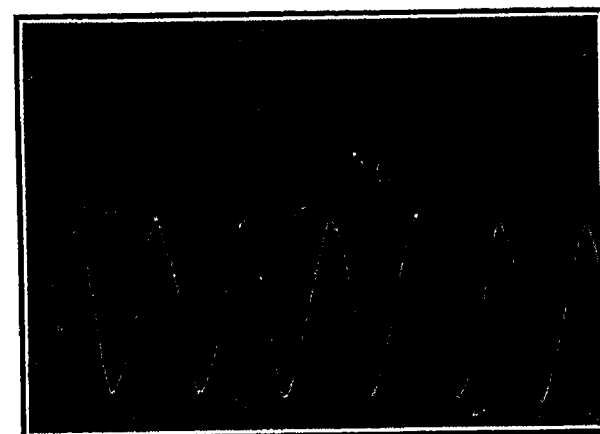


FIG. 3—RESIDUAL CURRENT ON IDLE LINE (LEAKAGE AND CHARGING CURRENT ONLY)

As requested by Mr. Smith, the following table indicates the magnitudes of generated harmonics observed in the case of one particular instrument when fundamental voltages were applied to its input circuit having frequencies different from those for which the input circuit was adjusted. A fundamental frequency of 1 volt was applied to the millivolt terminals in all cases, this being equivalent to 100 volts applied to the voltage terminals.

Input circuit adjusted for	Applied frequency	Generated harmonics per cent of fundamental		
		3rd	5th	7th
60 cycles	55	0.40	0.11	0.06
50 "	45	0.25	0.085	0.05
25 "	40	0.60	0.35	0.07
25 "	35	*	0.33	0.07
25 "	30	*	0.22	0.06

*Analyzer not arranged to be tuned at 90 and 105 cycles.

The following table gives additional data as to the magnitudes of generated third harmonics in a single instrument whose input circuit was adjusted for 60 cycles. In this latter case, the applied frequency was varied in small steps either side of 60 cycles.

1. *Residual Voltages and Currents in Power Systems*, A. I. E. E. Quarterly Trans., Vol. 48, January 1929, p. 92.

Applied frequency	Per cent generated third harmonic
58	0.185
58.5	0.13
59	0.085
59.5	0.052
60	0.04
60.5	0.05
61	0.077
61.5	0.12
62	0.165

Mr. Corbett in his discussion points out the fact that the accuracy of readings taken with analyzers of this type on operating power systems may be seriously impaired due to system frequency variations. Experience with these instruments on a large number of operating systems, both large and small, indicates that relatively rapid variations in the magnitudes of various harmonics under operating conditions are of considerably greater importance than the slower changes due to the frequency variations described by Mr. Corbett. It is possible with an indicating instrument of this type, however, to follow such variations closely and to obtain readings representing average conditions over as long a period of time as may be desirable. During the past few years a large amount of data has been obtained with these analyzers on various types of power systems and, in general, the data have been constant and their accuracy has been satisfactory. The figure of ± 0.4 cycle quoted as representative of frequency variations on operating systems is probably intended as an outside figure

and is consistent with the authors' experience. However, from observations of frequency recorders on a number of the larger systems it would appear that on such systems frequency variations, on an average, do not amount to more than from ± 0.1 to ± 0.2 cycle.

As further pointed out by Mr. Corbett, the analyzers described in this paper do not measure phase angles. In general, however, in inductive-coordination studies, for which these analyzers were primarily developed, a knowledge of the phase relations between the various harmonics is of secondary importance. Where such information is desired, it is often possible to obtain satisfactory data at the lower frequencies by means of the oscillograph, as discussed by Mr. Corbett. The oscillograms which he presents demonstrate quite clearly the magnitudes and relative phase angles of several third-harmonic residual currents. However, as he points out the magnitudes and phase angles of the higher harmonic components present can be obtained only by a laborious process of measurement and calculation. Furthermore, if the magnitudes are small the precision obtained is low. It was to obtain information as to the magnitudes of such relatively small but important higher harmonics, as well as the larger lower-frequency components, that the analyzers described in this paper were developed. As mentioned by Mr. Coleman in his discussion, by means of these analyzers as many as 2000 separate measurements of harmonic currents and voltages have often been made in a single day. From the standpoint of time required, the use of an oscillograph in such work would obviously be out of the question.

A New Automatic Synchronizer

BY F. H. GULLIKSEN¹

Associate A. I. E. E.

Synopsis.—The fundamentals of automatic synchronizing are discussed, and the requirements which must be met by the ideal synchronizer are outlined. The design and the principle of operation of two different models of a newly developed automatic synchronizer are described.

The paper treats the method by which, for any frequency difference within limits of present operating practise, either model of the synchronizer will cause the closing coil of the circuit breaker to be energized in advance of synchronism, by a time equal to that required to close the circuit breaker. The closing coil of the circuit breaker is, therefore, energized when the phase displacement between the voltages

of the two systems to be synchronized is such that, assuming the frequency difference between the two systems remains constant during the short time required to close the breaker, the breaker contacts will always be closed at the instant of zero voltage phase displacement.

The reasons for the excellent performance of these automatic synchronizers even when applied to connect systems with very erratic frequencies are outlined.

A series of tests is referred to, showing the superiority of automatic synchronizing in comparison with manual synchronizing, and the results obtained with the new synchronizer models in a generating station with propeller type waterwheels are described.

FUNDAMENTALS OF SYNCHRONIZING

The synchronizing of a-c. generators is one of the most exacting duties required of an operator in a manually operated generating station. When the operator is bringing a new unit on the line he has many duties, and his time is crowded. He must match the voltage of the machine with the line voltage, he must regulate the speed of the prime mover by hand until the frequency difference between the two sources to be paralleled is within the permissible synchronizing range, and at the same time the operator must closely watch the synchronoscope, indicating the phase displacement and frequency difference between the two sides of the breaker to be paralleled, and choose the proper moment to throw the control switch, closing the breaker, so that the relatively slow closing breaker will actually close its contacts at the point of zero phase displacement between the two system potentials.

Due to variations in the speed of the generator and since the frequency of most systems shows variations, the synchronoscope will often not rotate at uniform speed, and this makes the task of the synchronizing operator still more difficult to handle. The operator himself knows that a false move by a fraction of a second may wreck a machine worth hundreds of thousands of dollars, or at least may cause disturbances on the system so severe that important synchronous load connected to it may fall out of step. For this reason the influence of the human uncertainty element is more pronounced in non-automatic synchronizing than in other generating station operations where the result of a faulty move will not be as disastrous.

It has long been the trend within the field of electrical operations to try to eliminate the human element and substitute for it a mechanical device which is not affected by nerves and human emotions, and which always can be relied on to operate at the topmost rate of efficiency and performance. This is even more the

case when the mechanical device will do a better job than a skilled operator, and do it cheaper.

Automatic synchronizing stations have been in use for several years. Two different synchronizing methods have been applied, either the self synchronizing method or the automatic synchronizing method. In the self synchronizing method the machine is connected to the system without any field when the frequency of the machine is about 80 per cent of the system frequency. The field is then gradually applied and in this manner the incoming machine is pulled into step. In the automatic synchronizing method the synchronizing is done in the same manner as when manual synchronizing is being used. The automatic synchronizer takes the place of the operator and closes the breaker, while the frequency of the incoming machine is matched with the frequency of line by means of separate speed matching equipment.

The self-synchronizing method has been most commonly applied, especially in applications with erratic frequencies, because the characteristics of the automatic synchronizers previously available were such that it would require too long to synchronize the machine with the line if the frequencies of the two systems were not very stable. However, self synchronizing can usually not be applied when:

1. The capacity of the generator to be connected exceeds $\frac{1}{4}$ to $\frac{1}{3}$ of the capacity of the system.
2. Where important synchronous load connected to the station bus requires that the machine be connected to the system as smoothly as possible.
3. Where the generator to be connected is not equipped with damper windings.

Due to the increased use of the propeller type waterwheels and due to the general interest in automatic stations, a need was felt for a new automatic synchronizer that would synchronize even very erratic machines with the same accuracy and within a shorter time than a skilled operator at his best was able to do.

It may be advisable at this point to mention the

1. Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

Presented at the Summer Convention of the A. I. E. E. Swampscott, Mass., June 24-28, 1929.

various factors which are important in any synchronizing application.

When two synchronous generators are to be connected in parallel, the equalizing current between them in the paralleling moment will be zero if, when the breaker contacts engage:

1. The voltages are equal.
2. The phase displacement between the voltages is zero, and
3. The frequency difference is zero between the two systems to be connected.

The voltage equality will have to be taken care of by voltage regulating equipment outside the automatic synchronizer, and will not be discussed in this paper; but the effect of a voltage inequality on the performance of the automatic synchronizer will be mentioned later in this paper.

Zero-Phase Displacement. The equalizing current between the two sources in the paralleling moment will be proportional to the sine of the angle of phase displacement between the voltages of the two systems to be connected, and for smaller angles therefore, (below 45 deg.) the angle at which the breaker contacts engage will give an approximate check on the amount of equalizing current, and consequently the closing angle can be used as a measure of the performance of the synchronizer.

Zero-Frequency Difference. The third requirement mentioned above, the zero-frequency difference, is of a merely theoretical interest, because in the majority of practical applications zero-frequency difference cannot be obtained, at least not within a reasonable time. Consider a case where a generator is to be synchronized with a system. By means of speed matching equipment acting upon the governor of the prime mover the generator is brought up very close to synchronous speed. With an absolutely constant system frequency and with ideal speed matching equipment it would be possible to obtain zero-frequency difference and the ideal synchronizing conditions would then obtain when the phase displacement between the two voltages was zero. In practise, however, the sensitivity of the speed matching equipment is not absolute, and furthermore, even with large systems momentary frequency variations may occur due to load variations. For this reason the frequency difference in synchronizing applications will usually be fluctuating, often within a very wide range not seldom within ± 1 cycle, and in most applications zero frequency difference will merely obtain in a short instant when the speed of the generator is changing from leading to lagging or vice versa, and consequently an automatic synchronizer designed to close the breaker only when the frequency difference is zero, would not have much chance to complete the synchronizing operation.

Fortunately, however, in actual operating practise exact zero-frequency difference is not necessary. Smaller generators can be safely connected to the line

even with frequency differences as high as $\frac{1}{4}$ cycle per second, while larger units will require a lower frequency difference. It must, however, be required that the breaker contacts be closed at the point of zero voltage phase displacement. The underlying idea of the design of an automatic synchronizer is therefore to provide an apparatus that will close the breaker connecting two sources to be synchronized if the frequency difference between the two sources is below a predetermined value to be chosen for each particular application, and close the breaker at such a moment that, independent of the instantaneous frequency difference, the breaker contacts will always engage at the moment of zero phase displacement between the voltages, or at synchronism.

The factor that complicates the design of an ideal automatic synchronizer is the time element of the circuit breaker. There is always a certain time required from the energizing of the closing coil of a circuit breaker until the breaker contacts close. This time is practically constant for a definite breaker, but varies for different types and sizes of breakers from 0.2 sec. to 0.6 sec. Suppose that a breaker having a time element of 0.5 sec. is being applied to connect two systems, and that a frequency difference of $1/6$ cycle corresponding to one revolution of the synchroscope in 6 sec. is present. To obtain breaker closure at zero phase displacement with this breaker, at lockout frequency difference $1/6$ cycle the synchronizer must energize the breaker closing relay at a point 30 deg. in advance of zero-phase displacement.

Suppose now a machine with comparatively small inertia and excellent governor equipment is to be synchronized, and that the frequency difference during one revolution of the synchroscope change from $1/5$ cycle to $1/40$ cycle. One-fifth cycle is above the lockout frequency difference and the synchronizer would therefore not close at this frequency difference, but would close on the next beat at a $1/40$ -cycle frequency difference, and the result would be that the breaker contacts would close 25.5 degrees ahead of synchronism, and since at this point the voltage difference between the two sources to be connected is 43 per cent of the line voltage, considerable equalizing currents will result. To obtain correct closure at $1/40$ -cycle frequency difference, and assuming that the frequency difference remains constant during the short time of breaker closure, the synchronizer must energize the breaker closing relay at a point 4.5 degrees ahead of synchronism.

From the above considerations, the following requirements to be met by a successful automatic synchronizer can be summed up.

1. The synchronizer must operate only within a predetermined frequency difference. A single adjustment must be provided to vary the synchronizing range covered by the apparatus.
2. The synchronizer must energize the breaker closing relay in advance of zero phase displacement. The amount of advance must be proportional to the in-

stantaneous frequency difference. By one single adjustment it must be possible to vary the rate of change of advance to adjust the synchronizer for breakers with different closing time.

THE DESIGN OF THE NEW AUTOMATIC SYNCHRONIZER

In Fig. 1 is shown a front view of the new automatic synchronizer with the front glass cover removed. Two different models of this apparatus are available. The design and appearance of the two models are quite alike, but the principle of operation is different, one model being designed especially for applications with very erratic frequencies.

A schematic outline of the apparatus is shown in Fig. 2, and the following description of the two models

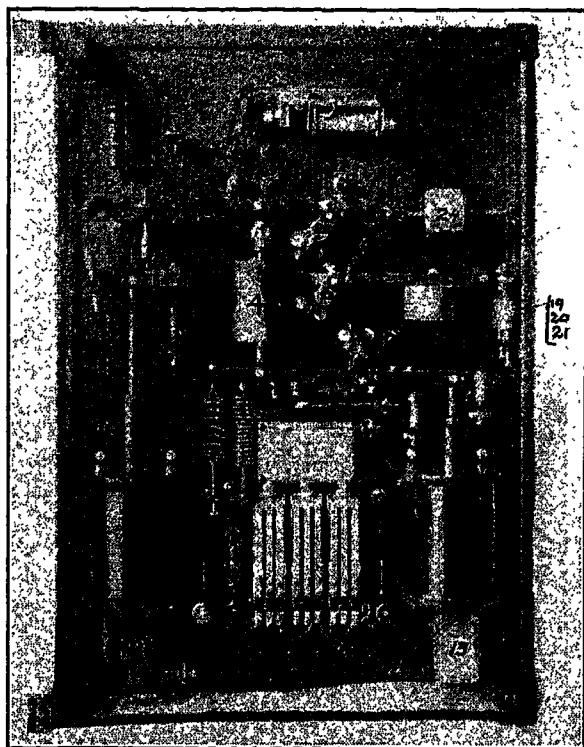


FIG. 1—FRONT VIEW OF THE AUTOMATIC SYNCHRONIZER WITH COVER GLASS REMOVED

refers to this figure. The models will be referred to as type XY-11 and type XY-12, the latter being the model designed for erratic frequency applications.

The synchronizer consists essentially of two independent coil-core lever systems and four d-c. relays of the telephone type. Referring to Fig. 2 the one lever system is made up of dashpot 12, coil 11, core 10, lever 22, fulcrum 6, springs 19, 20, 21, and lower contact B. When coil 11 is deenergized, the lever system is balanced by means of a counterweight and spring 20 so that lower contact B barely touches upper contact B, when upper contact B is in its highest position. Core 10 is assembled so that when coil 11 is energized the core will be pulled downwards. The downward travel of core 10 is limited by means of a stop post 5 to prevent the springs 19, 20, 21 from being overextended.

Coil 11 is connected in series with coil 14 across the dark lamp beat voltage between the two systems, as can be seen in Figs. 8 and 10, and consequently the

voltage across the coil will be zero when the phase displacement is zero, and will be maximum (220 volts) when the phase displacement is 180 deg. For small phase displacements (up to 50 deg.) the voltage difference or beat voltage across the coils will be ap-

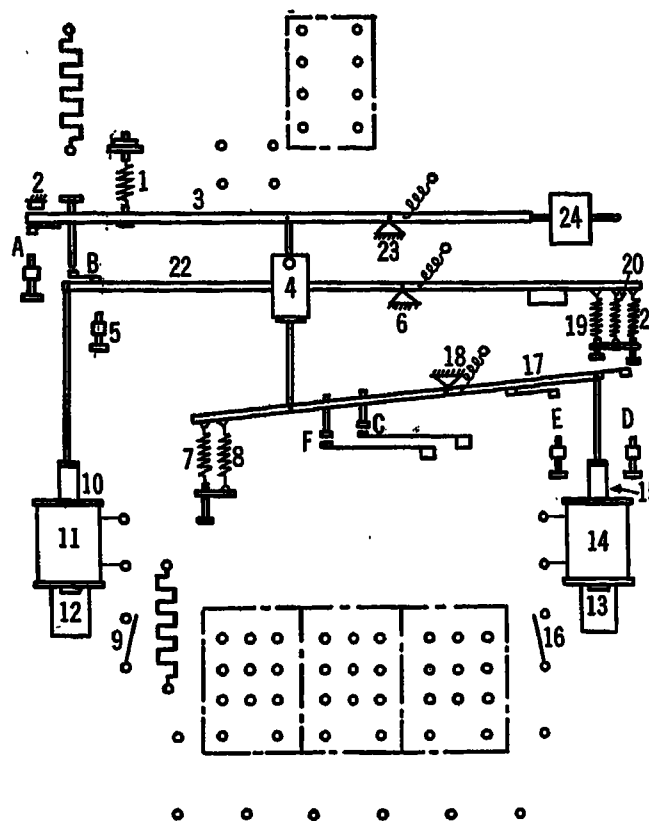


FIG. 2—SCHEMATIC OUTLINE OF AUTOMATIC SYNCHRONIZER

proximately proportional to the phase angle provided the voltage waves of the two systems are sine waves, and therefore, assuming that for any impressed voltage across the two coils the ratio between the two impedances is constant, the voltage across coil 11 will be proportional to the angle of phase displacement as shown in Fig. 3.

The pull on core 10 increases when the core travels downward into the coil. To obtain a travel of lower

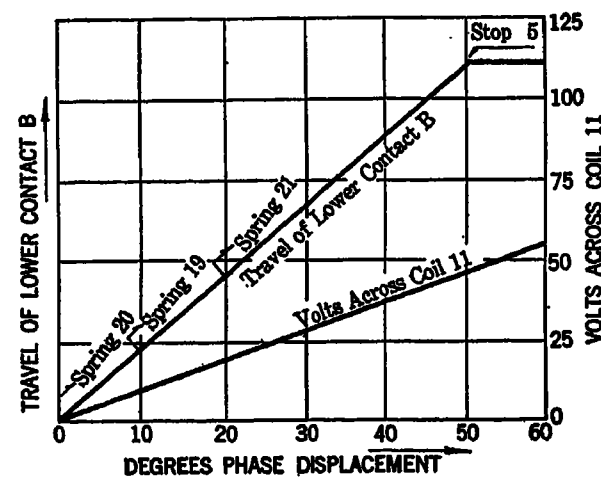


FIG. 3—VARIATION OF VOLTAGE ACROSS COIL 11 AND OF TRAVEL OF LOWER CONTACT B

contact B which is proportional to the angle of phase displacement, springs 19 and 21 are applied to come into action in sequence as indicated on travel curve for contact B in Fig. 3. At 50 deg. phase displacement lever 22 reaches stop post 5, and for phase displacements exceeding 50 deg. lever 22 will be resting on post 5;

for phase displacement within 50 degrees contacts *B* will move in proportion to the change in phase displacement.

Dashpot 12 is applied to dampen the mechanical vibrations on the lever system resulting from a high frequency difference. The damping of the dashpot is small, however, and for frequency differences of an order of 1 to $1\frac{1}{2}$ cycles the lever system will be nearly undamped. In order to obtain the proper performance of the synchronizer it is important that the lever system be absolutely undamped for any frequency difference

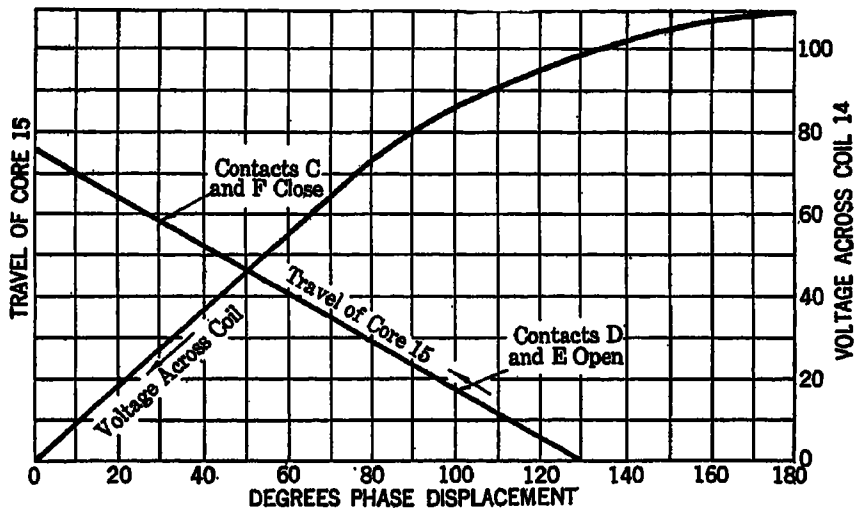


FIG. 4—RELATIONSHIP BETWEEN PHASE-ANGLE DISPLACEMENT VOLTAGE ACROSS COIL 14 AND TRAVEL OF CORE 15

within the applicable synchronizing range. How this feature is obtained through the interaction between the series connected coils 11 and 14 will be explained later in this paper.

Lever system No. 1 (described above) which is lightly damped, provides essentially the means for checking the instantaneous phase displacement between the voltages of the two systems to be connected, while the more heavily damped lever system No. 2 provides the means for obtaining the advance closure of the breaker proportional to the instantaneous frequency difference, and provides the means to prevent synchronizing if the frequency difference is above the permissible synchronizing range.

Lever system No. 2 consists of two lever assemblies, connected by means of the air dashpot 4. Lever 3 supported by fulcrum 23 is balanced by means of spring 1 and counterweight 24 to barely touch stop post 2. Upper contacts *A* and *B* are mounted on lever 3. Lever 17 is supported by fulcrum 18, and balanced by means of springs 7 and 8 against the pull exerted by coil 14 on core 15.

When the phase displacement between the voltages of the two systems is 180 deg., core 15 is attracted by coil 14 and in its lowest position. If the phase displacement is decreased, the pull on the core will decrease, and finally at 130 deg. phase displacement the pull on core 15 is equal to the combined pull of the springs 7 and 8. If the phase displacement is further decreased, core 15 will start to travel upwards. The

springs 7 and 8 are so designed that the travel of core 15 will be proportional to the angle of phase displacement as shown in Fig. 4.

Upper contacts *E* and *D* are spring mounted, and for this reason contacts *E* and *D* will not open until the voltage phase displacement is reduced to 100 deg., and because lever contacts *C* and *F* are spring mounted the contacts *C* and *F* will close when the phase displacement is approximately 30 degrees and will remain closed while the core 15 is completing its travel, reaching its highest position at zero-degree phase displacement.

It will be understood that core 15 will tend to assume a position in relation to coil 14, which will primarily be dependent upon the instantaneous phase displacement between the voltages of the two systems to be connected; but the position of core 15 will also be dependent upon the rate of change of phase displacement, or in other words dependent upon the instantaneous frequency difference between the two systems.

The reason for this latter feature is the heavy damping provided by dashpots 4 and 13. Due to this damping the position of core 15 and consequently also lever 17 will be lagging if a frequency difference is present, in relation to the position lever 17 would assume if the frequency difference were zero. The amount of lag when the phase displacement is decreased from 130 deg. towards zero will be proportional to the frequency difference and the effect of this is to reduce the amplitude of travel of core 15 and its con-

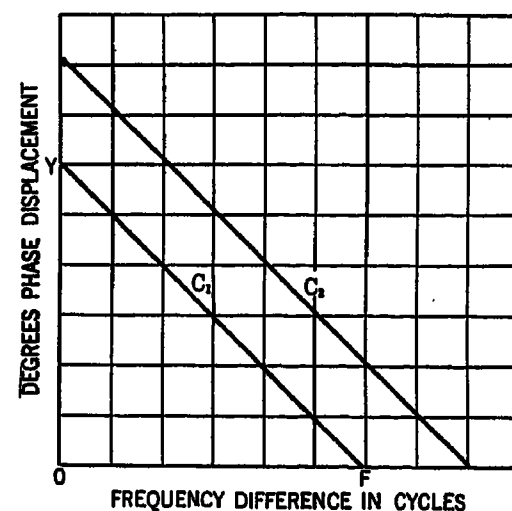


FIG. 5—CLOSING CHARACTERISTIC FOR CONTACTS *C* FOR TWO DIFFERENT ADJUSTMENTS OF THE CONTACTS

nected lever 17, by an amount which for low values of frequency difference will be proportional to the frequency difference. Consequently the closing characteristic for contacts *C* will be a straight line as shown in Fig. 5. When the frequency difference is zero contacts *C* may close at *Y* degrees phase displacement. For frequency differences above *F* cycles the contacts *C* will not close during one rotation of the phase-displacement vector. The point *Y* can be moved upwards or downwards by changing the setting of contacts *C*. If upper contact *C* is adjusted downwards in relation to lever 17 the point *Y* in Fig. 5 will move upwards and a

new curve C_2 will obtain. The adjustment of contacts C will not change the slope of the closing characteristic; the slope being entirely dependent upon the damping in dashpots 4 and 13, increased damping will increase the slope, or in other words move point F towards zero while point Y is kept in place.

Contacts F will have a closing characteristic similar to contacts C ; while contacts E and D will close at 100 deg. phase displacement when the frequency difference is zero. For increasing frequency difference contacts E and D will close nearer to the point of phase opposi-

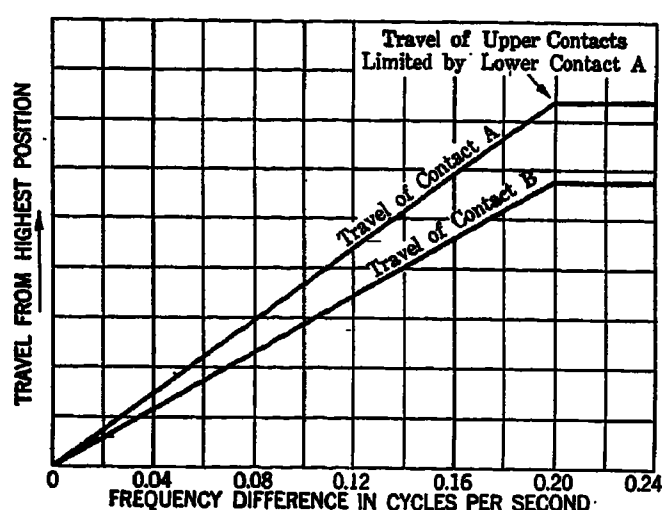


FIG. 6—TRAVEL OF UPPER CONTACTS A AND B

tion (180-deg. phase displacement) and for a certain definite frequency difference the contacts will not close at all during one phase rotation. The closing characteristic of contacts E and D will not be a straight line. The shape of the curve is immaterial in respect to the performance of the synchronizer.

When the phase displacement between the two system voltages is decreasing, core 15 as previously mentioned will travel upwards with a velocity proportional to the instantaneous frequency difference, as long as the frequency difference is comparatively low, *i. e.*, of an order of three cycles or less. Since the plunger of dashpot 4 is connected to lever 17 the velocity of the downward movement of the plunger will be proportional to the instantaneous frequency difference. When plunger 4 is being moved downwards, the dashpot 4 will exert a certain downward pull on the left hand side of lever 3, and consequently lever 3 will rotate counter clockwise until the pull of dashpot 4 is balanced by the increasing tension on spring 1. The pull of dashpot 4 on lever 3 is proportional to the velocity of travel of plunger 4. The extension of spring 1 is proportional to the tension of the spring, and for this reason the angular movement of lever 3 is proportional to the pull of dashpot 4, furthermore, proportional to the velocity of travel of plunger 4 and consequently proportional to the instantaneous frequency difference between the two systems to be paralleled.

Upper contacts A and B are mounted on lever 3, and referring to above considerations it will be obvious that contacts A and B , when the phase displacement is decreasing from 130 deg. towards zero will assume a

position in space, in relation to their highest position, which will be proportional to the instantaneous frequency difference, or in other words, the position of contacts A and B will be the lower the higher the frequency difference is, as will appear from Fig. 6.

The impedances of coils 11 and 14 are equal for any phase displacement angle below 50 deg. if the frequency difference is zero. The impedance of coils 11 and 14 will decrease when the cores travel upwards out of the coils. Since core 15 is heavily damped, the core will be lagging considerably in relation to the momentary voltage phase displacement when the phase displacement is decreasing. The amount of lag of core 15 is proportional to the instantaneous frequency difference; for this reason the ratio between the instantaneous voltage drops across coil 14 and coil 11 will increase with increasing frequency difference, and since the total voltage drop across the two series-connected coils is dependent upon the phase displacement, the voltage drop across coil 11 will decrease with increasing frequency difference, so that core 10 will tend to assume a slightly advanced position, and in this manner, the small amount of damping in dashpot 12 is compensated for.

In Fig. 7 are shown two various closing characteristics for contacts B . When the frequency difference is zero, contacts B will close at the point of zero phase displacement. For any definite frequency difference the contacts will close at a point in advance of synchronism,

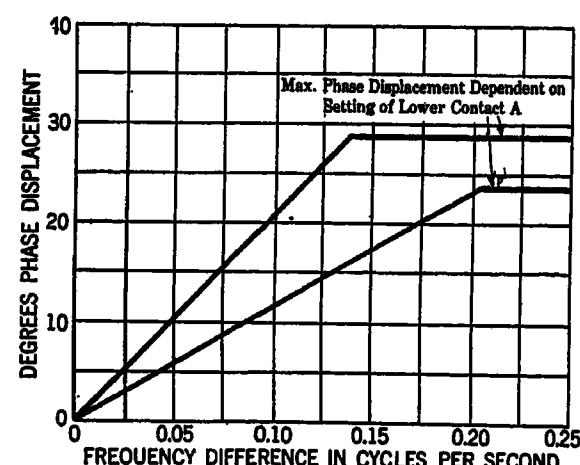


FIG. 7—CLOSING CHARACTERISTICS FOR CONTACTS B FOR VARIOUS ADJUSTMENTS OF DASHPOT 4 AND LOWER CONTACT A

the amount of advance being proportional to the instantaneous frequency difference.

By adjusting the amount of damping in dashpot 4, the slope of the curves in Fig. 7 varies, and the synchronizer can thus be adjusted to energize the closing relay of any circuit breaker connecting two systems to be synchronized at such a point in advance of synchronism, that allowing for the time element of the breaker the breaker contacts will close at the point of zero phase displacement, assuming that the closing time of the breaker is practically constant and further assuming that the frequency difference does not change during the short time required to close the circuit breaker.

This method of obtaining breaker closure at the point

of zero phase displacement for any frequency difference within the permissible synchronizing range is applied in both models of the automatic synchronizers. The method in which breaker closure is prevented if the frequency difference exceeds the selected lockout frequency difference, however, is different for the type XY-11 synchronizer than for the type XY-12 synchronizer.

Method of Lockout. The XY-11 synchronizer is arranged so that the breaker will be closed if the frequency difference during the last 90 deg. of its phase angle does not exceed the selected lockout frequency difference, while the XY-12 synchronizer will connect the breaker and synchronize the two systems if the frequency difference at a point 35 deg. ahead of synchronism is lower than the selected lockout frequency difference. Thus it may be seen that the XY-12 synchronizer is especially well adapted for application with very erratic frequencies.

In Fig. 6 was shown the travel frequency characteristic of upper contact A, and it was pointed out that upper contact A when the angle of phase displacement between the two system voltages was decreasing from 130 deg. towards zero would assume a position in relation to its highest position which would be proportional to the instantaneous frequency difference. Lower contact A is a stationary contact mounted on the base of the synchronizer. For a definite setting of lower contact A there will always be a definite frequency difference above which contacts A will engage during one rotation of the phase displacement vector. This feature is used in the lockout scheme for the XY-11 synchronizer as shown in the diagram of connections of the automatic synchronizer type XY-11 (Fig. 8), which is arranged so that whenever contacts A have been engaged it is necessary for the phase angle to exceed 100 deg. once before the synchronizer will again be able to close the paralleling breaker.

A clear conception of the function of the lockout contacts A may be obtained by going through the operating sequence for the various relays of the automatic synchronizer type XY-11 for frequency differences above and below the selected lockout frequency difference.

Assuming that the proper connections to the two systems have been made, and that the master relay connecting the synchronizer to the control circuits close when a frequency difference of 5 cycles exists between the two systems, none of the relays, T_1 , T_2 , T_3 will be energized because lever 17 due to the damping effect of dashpots 4 and 13 will never come into a position to close contacts D. When the frequency difference is reduced to approximately 3 cycles, contacts D will engage, closing relay T_1 which will seal itself in. Nothing further happens until the frequency difference is reduced to $\frac{1}{2}$ cycle. At this frequency difference contacts C engage at approximately zero phase displacement and relay T_2 is closed and sealed in. At a point 260 deg. ahead of synchronism, contacts E will close and relay T_3 will be energized and sealed in.

Supposing now the frequency difference is lowered to $\frac{1}{7}$ cycle and that contact A has been adjusted just not to close at this frequency difference, then the breaker closing relay will be energized at the proper phase advance when contacts B engage, and the breaker main contacts will engage at the point of zero phase displacement. If, however, the frequency difference should happen to increase above the safe synchronizing limit,

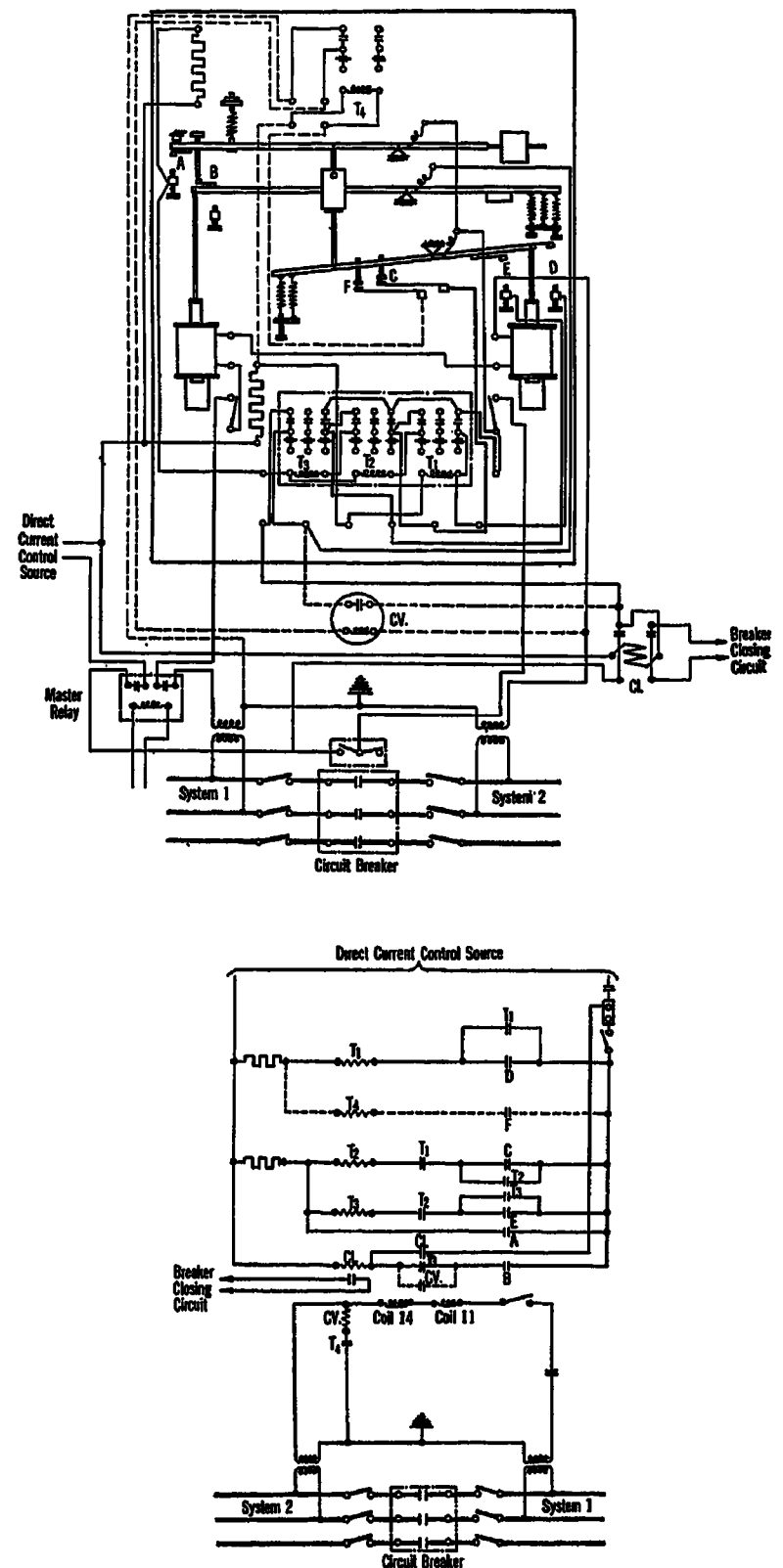


FIG. 8—DIAGRAM OF CONNECTIONS AND SCHEMATIC DIAGRAM FOR AUTOMATIC SYNCHRONIZER TYPE XY-11

in this case supposed to be $\frac{1}{7}$ cycle, then contacts A will engage before contacts B close, relays T_2 and T_3 will be shunted by contacts A and opened, and in this manner synchronizing is positively prevented.

The lockout feature of the XY-12 synchronizer is based on the change in closing sequence of contacts B and C when the frequency difference passes through the lockout frequency difference for which the synchronizer

has been adjusted. In Fig. 9 is plotted the closing characteristic for contacts *B* and *C* in the same scale. Considering curves *B* and *C*, it may be seen that for frequency differences exceeding F_1 cycles, contacts *B* will close ahead of contacts *C*; while contacts *C* will close ahead of contacts *B* for frequency difference lower than F_1 cycles. The slope of curve *B*, as previously mentioned, is adjusted to suit the time element of the circuit breaker, and the adjustment is made by changing the amount of damping in dashpot 4. When dashpot 4 has been adjusted the slope of curve *C* is given, but the location of the curve is dependent upon the adjustment of contacts *C*. By adjusting upper contacts *C* downwards in relation to lever 17, a curve C_2 may be obtained, and consequently the synchronizer will be able to connect the breaker at a higher frequency difference, for example F_2 cycles.

The schematic diagram of connections for the type XY-12 synchronizer is shown in Fig. 10. For frequency differences below 3 cycles contacts *D* will close at some point 100 to 180 degrees out of phase, and energize

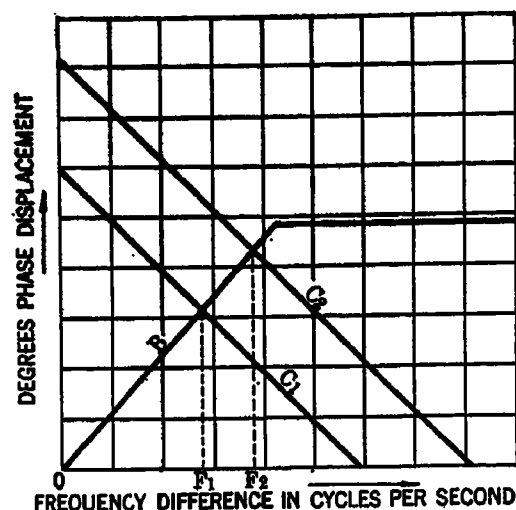


FIG. 9—CLOSING RELATIONSHIP CONTACTS *B* AND *C*

relay T_1 , which seals itself in through the back contacts of relay T_2 . As long as the frequency difference is above the selected lockout frequency difference, contacts *B* will close before contacts *C* close, and relay T_2 will be closed, thus opening relay T_1 . Contacts *E* which close simultaneously with contacts *D* are connected to shunt the relay T_2 to be sure that relay T_2 will open once during each phase rotation. If the instantaneous frequency difference at a point 35 deg. ahead of synchronism is lower than the selected lockout frequency difference relays T_2 and T_3 will be closed, provided relay T_1 has already been closed, and hence the breaker closing relay will be energized and the breaker will be closed. The operating sequence under these conditions is: Contacts *D* close approximately 260 deg. ahead of synchronism, and close relay T_1 which seals itself in across the back contacts of relay T_2 .

At a point within 60 deg. phase displacement, dependent upon the frequency difference contacts *C* close and operate relay T_3 which seals itself in while one pair of the contacts of T_3 parallels the T_2 back con-

tacts in series with relay T_1 . When the phase displacement is further reduced, contacts *B* close at the proper phase advance proportional to the instantaneous frequency difference, and energize relay T_2 which completes the closing circuit of the breaker closing relay so that the breaker will close and synchronize the two systems.

It will appear from above description of the two

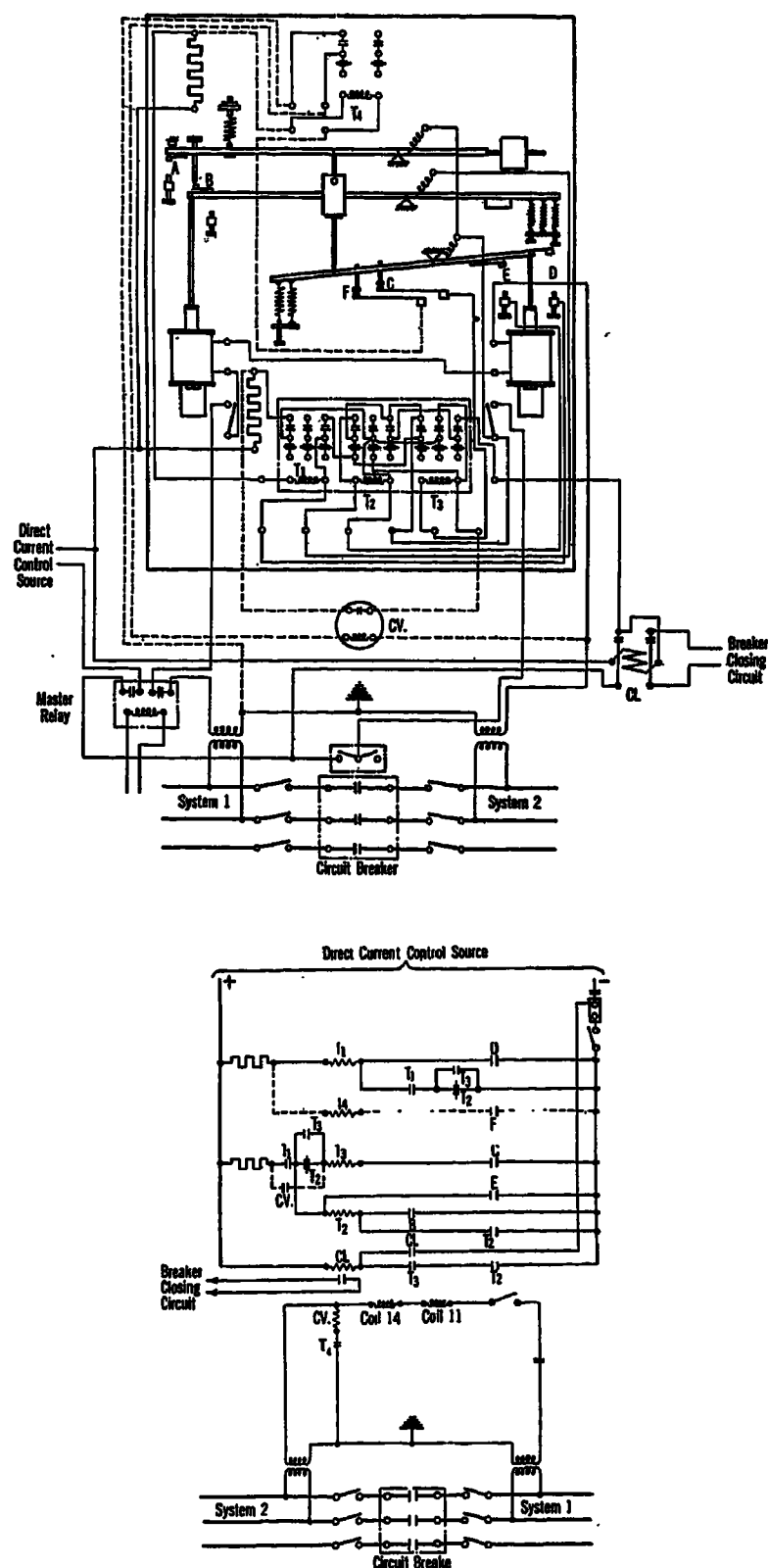


FIG. 10—DIAGRAM OF CONNECTIONS AND SCHEMATIC DIAGRAM FOR AUTOMATIC SYNCHRONIZER TYPE XY-12

synchronizer models that to make the synchronizer operate it must be required that the voltage phase vector make $1\frac{1}{2}$ revolutions before the synchronizer will be able to synchronize the two systems. For this reason the synchronizers as described above will not be able to synchronize if the breaker to be closed is not the first tie between two systems, since in this case the frequency difference will be zero, and no phase rotation

will obtain. This condition is taken care of by supplying an external relay to be energized by contacts T_4 . This relay operates on a-c. voltage and will when energized close its contacts after a predetermined time delay. The relay contacts will open when the relay is deenergized.

Contacts F are adjusted to close within ± 15 degrees phase angle displacement, and from Figs. 8 and 10 it may be seen that by means of the contacts of the relay marked CV , the synchronizer will operate if the frequency difference is zero for example, when the synchronizer is used in a line to line synchronizing application. It should be noted that if a frequency difference exists contacts F will not remain closed long enough to close relay CV , and operation of the synchronizer will therefore be as previously described.

The performance of an automatic synchronizer if the voltages of the two systems to be paralleled are not equal is of interest, since a voltage inequality can be experienced in various types of installations.

As long as a frequency difference exceeding 1/10 cycle per second exists between the two systems the closing

but will close the breaker too early when equal voltages obtain on the two systems. The amount of degrees early closure will be equal to $\frac{1}{2}$ deg. per per cent voltage inequality, and will therefore be negligible in most applications.

APPLICATION

The automatic synchronizer models described above are designed to operate on potential transformers with 110 volts secondary voltage. The average load on each potential transformer is 40 volt-amperes. Taps have been supplied on the resistors in the control circuit of the apparatus so that connections can be made to 48 volts or 125 volts d-c. control source. For 250 volts d-c. control voltage an external resistor is supplied. The back contacts of the circuit breaker are connected in series with the d-c. control circuit, so that the telephone relays of the synchronizer are deenergized when the breaker is closed.

The synchronizer will energize the breaker at a maximum advance of 35 deg. To obtain proper performance of the synchronizer the maximum frequency difference for which the synchronizer should be adjusted to operate and close the breaker is given by

$$\text{equation } F = \frac{35}{T \cdot 360} \text{ where } T = \text{breaker closing time}$$

in seconds.

For most applications it is desirable for operating reasons to keep the lockout frequency difference well within this limit.

ADJUSTMENTS

The adjustments of the automatic synchronizer are quite simple. The apparatus is calibrated and tested in the factory under true operating conditions, and the field adjustments necessary are the adjustment of the amount of advance to suit the particular breaker applied and the adjustment of the lockout frequency difference.

The Advance Adjustment. This adjustment is made at approximately 1/10 cycle frequency difference between the two sources to be connected, while the line switch is open so that the breaker can be closed without paralleling the two systems. A lamp with a small time lag or a quick acting relay is connected in series with one pair of the main contacts of the circuit breaker, and is energized by the d-c. control source. This lamp or relay is placed close to the synchronoscope and by watching the synchronoscope it is possible to see whether the breaker closes too early or too late. The adjustment of the air valve of dashpot 4 is varied until the breaker contacts close at zero phase angle displacement.

The Lockout Adjustment. The speed of one source is adjusted to give the highest frequency difference at which it is wanted to synchronize, and the lower contact A for type X Y-11 and upper contact C for type X Y-12 is adjusted so that the telephone relays of the synchronizer is just not locked out at this frequency difference.

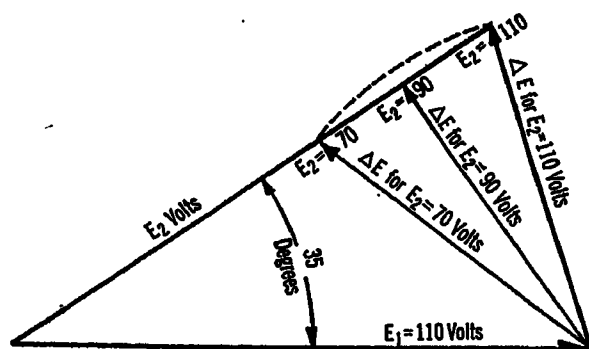


FIG. 11—THE VARIATION OF THE VOLTAGE ACROSS THE SYNCHRONIZER A-C. COILS

When a voltage inequality is present between the two systems while the phase displacement between the voltages is 35 degrees

error is negligible, due to the fact that the position of lower contact B at 35 deg. phase angle displacement will be approximately the same whether the voltages of the two systems are equal or unequal. This is due to the fact that the voltage impressed across the coils will vary inconsiderably when the phase angle displacement is 35 deg., as can be seen from Fig. 11. In this figure are shown the two system voltages E_1 and E_2 at 35 deg. displacement, and also the vectorial voltage difference ΔE for various values of E_2 while E_1 is kept constant.

For a definite voltage inequality there is a minimum frequency difference below which the synchronizer will not operate. This condition is taken care of in application of line to line synchronizing by permanently advancing upper contact A , so that contacts A will barely engage at zero phase angle displacement when the maximum voltage inequality between the two systems obtain. With this adjustment the synchronizer will perform perfectly at the maximum voltage inequality and close the breaker at zero phase displacement;

COMPARATIVE TESTS BETWEEN HAND SYNCHRONIZING AND AUTOMATIC SYNCHRONIZING

A series of tests was made with the X Y-11 type synchronizer to determine the performance of the synchronizer and compare it with the performance of a skilled operator. A 3000-kv-a., 25-cycle, three-phase motor generator set was arranged to be synchronized with a

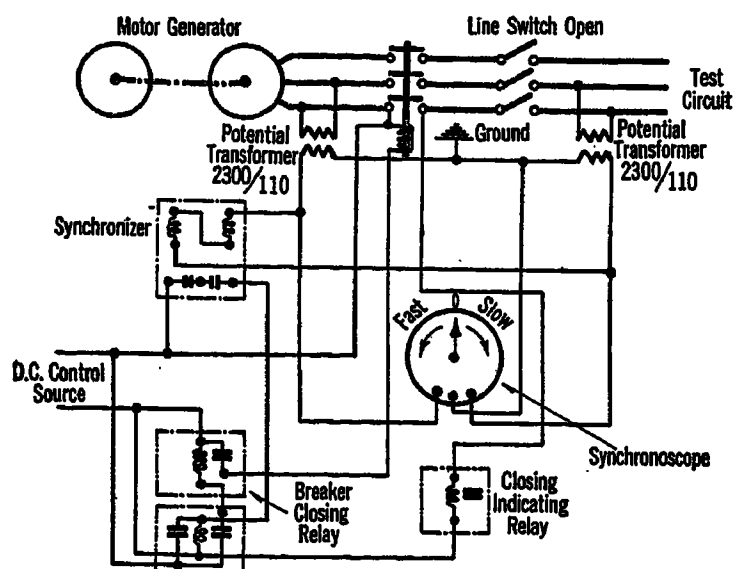


FIG. 12—CONNECTIONS FOR COMPARATIVE TESTS

25-cycle test circuit with the connections shown in Fig. 12. The frequency of the test circuit showed some variations due to load variations; the closing time of the oil circuit breaker used during the test was measured by means of a cycle counter. It was found that the time required from the moment the contacts of the synchronizer closed until the main contacts of the circuit breaker engaged was 0.6 sec. The speed of the motor generator set was regulated by hand to give

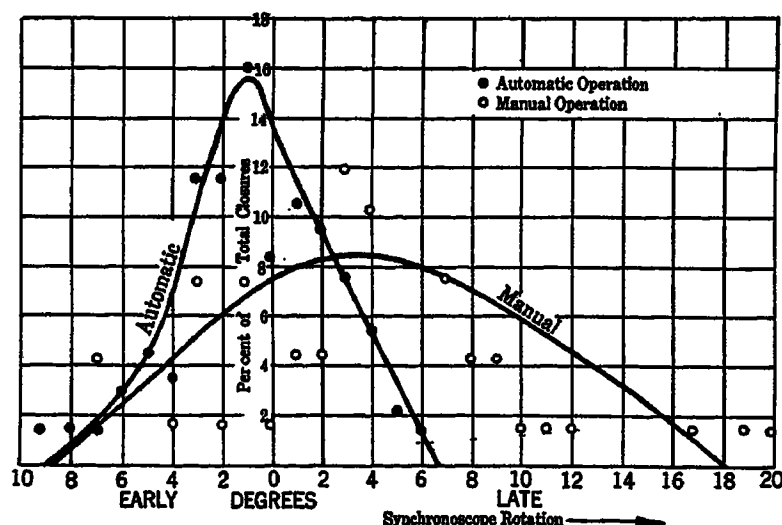


FIG. 13—RESULTS OF COMPARATIVE TESTS

various beat frequencies within the lockout frequency limit for which the synchronizer was adjusted. A quick operating relay (closing time 0.009 sec.) was used as a closing indicating relay and was connected so that it would operate when the main contacts of the circuit breaker engaged. This relay was held in the hand of one of the men conducting the tests, and the position of the synchronoscope pointer was read by him at the instant he felt the indicating relay operating.

With the automatic synchronizer in operation 193 readings were taken, and 67 readings were taken with hand operation.

The result of the tests is shown in Fig. 13, which shows the percentage of the total number of operations for which the circuit breaker contacts would close at a certain voltage phase displacement. The curves show the superior accuracy of the automatic synchronizer as compared with the performance of a skilled operator synchronizing by hand. The results for manual operation show that an operator is liable to close the circuit breaker too late. This would be even more the case for applications with erratic frequency and for such applications the comparison between automatic synchronizing and hand synchronizing would be still more favorable for the automatic synchronizer. From Fig. 13 may be seen that the automatic synchronizer would never close the breaker main contacts at a wider angle than 9 deg., while the operator happened to close

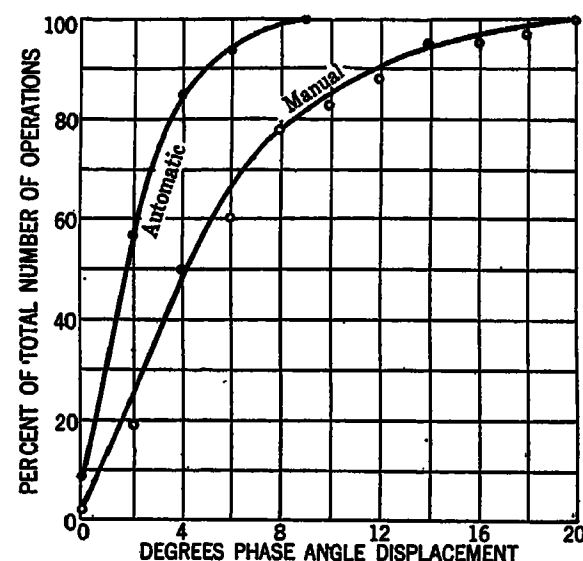


FIG. 14—A COMPARISON OF AUTOMATIC AND MANUAL SYNCHRONIZING

the breaker as much as 20 deg. too late. The curves do not indicate the fact that automatic closure required much less time than hand closure, since the operator would always wait for smaller frequency differences before he would synchronize; while the automatic synchronizer would close the breaker the first time the frequency difference was below the lockout frequency difference $1/7$ cycle.

The same test results as given in Fig. 13 are plotted in a different way in Fig. 14. The curves of Fig. 14 show the per cent of total number of operations for which the circuit breaker contacts close within a certain number of degrees of synchronism. For example, when automatic synchronizing was used the circuit breaker contacts would close within 2 deg. or less of synchronism for 56 per cent of the total number of operations, while with manual synchronizing the operator succeeded in getting the same good results for only 19 per cent of the total number of operations.

FIELD TESTS

Through the courtesy of the Kentucky Hydro Electric

Company a series of tests was made with the two automatic synchronizer types XY-11 and XY-12 at the Hydro Electric Generating Station at Dam No. 7, Kentucky River. This station is equipped with three generators, driven by propeller type waterwheels rated 1000 hp., 150 rev. per min. at 15 ft. normal water head. The generator rating for each unit is 850 kv-a. at 80 per cent power factor, 60 cycles, 150 rev. per min. The inertia of the units is low and due to the inherent characteristic of the hydraulic equipment, the frequency of the generator to be synchronized is very erratic in spite of the excellent condition of the installed governor equipment. The time element of the circuit breakers of the station was measured and found to be 0.25 sec.

The automatic switching equipment of the station was arranged so that any one of the three generating units could be started up by pressing a push button on the switchboard, or by means of supervisory equipment

controlled from a distant dispatcher's office. After a unit had been started up the automatic synchronizer was given control when the speed of the generator was high enough to allow the generator voltage to build up to normal. The time interval from the moment when a unit was started up until the synchronizer was given control was practically constant for each individual unit, but showed some variations for the three different units due to the various adjustments of the time delay of the voltage relays connected to give the synchronizer control.

With the XY-11 synchronizer in service 19 different synchronizing operations were made, while 25 different synchronizing operations were made with the XY-12 synchronizer in service. By means of a stop watch the total synchronizing time, from the start of a unit until breaker closure, was measured, and is given in column 2 of Table I. The time required from the start of a

TABLE I
FIELD TEST RESULTS

1	2	3	4	5	6	7
Test No.	Time in seconds from start of unit until breaker closure	Time in second from start of unit until synchronizer was given control	Time in second from energizing synchronizer until breaker closure	Breaker closure degrees phase displacement	Unit No.	Synchronizer model
1	105	40	65	5	3	XY-11
2	240	40	200	0		
3	75	40	35	15		
4	190	40	150	0		
5	70	40	30	0		
6	60	40	20	5		
7	70	40	30	5		
8	75	40	35	0		
9	70	40	30	5		
10	135	35	100	0	1	
11	130	35	95	5		
12	60	35	25	0		
13	80	35	45	0		
14	45	35	10	0		
15	55	35	20	10		
16	95	35	60	5		
17	110	35	75	0		
18	60	45	15	0	2	
19	115	45	70	5		
20	60	45	15	0	2	XY-12
21	120	45	75	15		
22	140	45	95	15		
23	55	45	10	0		
24	55	45	10	5		
25	70	45	25	5		
26	75	45	30	5		
27	65	45	20	10		
28	65	45	20	0		
29	45	35	10	0	1	
30	45	35	10	10		
31	60	35	15	0		
32	65	35	30	0		
33	45	35	10	5		
34	45	35	10	0		
35	45	35	10	0		
36	90	40	50	0	3	
37	75	40	35	0		
38	70	40	30	15		
39	85	40	45	0		
40	80	40	40	15		
41	65	40	25	0		
42	90	40	50	5		
43	65	40	25	10		
44	60	40	20	0		

machine until the synchronizer was connected is given in column 3, and the time during which the synchronizer was in operation is given in column 4. The phase displacement between the voltages in the moment of breaker closure as read on a synchronoscope is given in column 5.

From column 4 of Table I can be found that, with the XY-11 synchronizer in service the average time required to synchronize a machine was 58 sec., while the maximum synchronizing time during 19 operations was 200 sec. With the XY-12 synchronizer in service the average synchronizing time is found to be 30 sec., and the maximum time during 25 operations 95 sec.

During these tests the machine frequency was very erratic; in fact, the synchronoscope pointer was never seen to rotate at uniform speed for one full revolution, and the frequency difference seldom remained within the selected lockout frequency difference ($1/5$ cycle) for more than 10 sec. Due, however, to the proportional advance incorporated in the synchronizer models, the synchronizer would never close the breaker farther off synchronism than 15 deg. The average closing point for the XY-11 synchronizer, as given in column 5, Table I, was found to be at 2.9 deg. phase displacement, and the average closing point for the XY-12 synchronizer was found to be at 4.8 deg. phase displacement.

The type XY-12 synchronizer was permanently

installed in this station, and a series of synchronizing tests was made with the installed equipment to determine the time required to synchronize the whole station to the line. During the tests the push buttons of all three units were pressed simultaneously. Unit No. 1 would then start up. As soon as unit No. 1 reached normal voltage the synchronizer would be connected and the machine synchronized properly with the line. Units No. 2 and 3 would then start up simultaneously, and unit No. 2 was synchronized when the proper synchronizing conditions obtained. When unit No. 2 went on the line the synchronizer was switched over to unit No. 3 which would be synchronized.

During 7 different tests it was found that the type XY-12 synchronizer would connect all three generating units to the line in an average time of 159 sec., while the maximum synchronizing time was found to be 194 sec., and the minimum synchronizing time 119 sec. It should be noted that these data cover the time required to bring all three units up from zero speed to normal speed and to synchronize each unit individually with the line.

ACKNOWLEDGMENT

The writer wishes to express his appreciation for valuable suggestions received from Mr. J. H. Ashbaugh and Mr. H. C. Nycum.

High-Frequency Portable Tools and Equipment

BY C. B. COATES¹

Member, A. I. E. E.

Synopsis.—This paper presents practical information regarding the application of high-frequency (180-cycle) induction motors with low-resistance rotors to portable electric tools.

In order to compete with existing tools it became necessary to increase the rotor speed above that of 60 cycles, and 180 cycles per second was adopted as commercially practical. Several advantages are shown. There is a smaller drop in speed with this

type of motor, than with the d-c. or the universal motor, and because of this, greater power is developed. The life of the cutting tools is longer due to the better speed regulation. Less weight and lower maintenance costs result from this application.

Several new tools for special work are described. The desirable regulation of the frequency converter or motor generator is given as not exceeding 8 per cent.

THE application of the term "high-frequency" to portable tools and equipment is, no doubt, a misnomer in view of the extremely high radio and other frequencies generally understood to come within the scope of this term. As a matter of fact, the frequency now generally employed in so-called high-frequency portable tools is only three times the usual commercial frequency of 60 cycles per second. However, as the name has come to be quite generally accepted as applied to this class of tools, it will be used here.

In order to have a basis for comparison, it is desirable to make some reference to portable tools in general, so that reasons may be shown for this radical departure from the old standards.

OLDER TYPES OF TOOLS

Electric drills of the portable type were introduced over 25 years ago and were wound for operation on direct current, to conform to the prevailing conditions in the industrial plants at that time. These tools were generally series wound, but several years later the larger sizes were compound-wound to give better speed regulation, which means higher armature speed at full load with limited free speed and consequently greater brake horsepower.

This was a step in the direction of the high-frequency tool characteristics and it may be of interest, in passing, to note a very satisfactory method of applying compound windings to the larger d-c. drills, as adopted several years ago by one manufacturer of portable tools and still used. Fig. 1 shows the structure of the field and armature of this motor. There are four mechanical poles but only two electrical poles, *N* and *n* forming the north pole and *S* and *s* the south pole. Series coils are placed on poles *N* and *S* and shunt coils on poles *n* and *s*. The armature revolves in the direction indicated by the arrow. When the motor is subjected to a heavy load the cross magnetization of the field, caused by the large armature currents, tends to deplete the magnetism in the trailing pole tips of *N* and *S* and to build it up in the leading tips of *n* and *s*. The

gap between the pole faces of like polarity, of course, introduces reluctance into the path of this cross-magnetization. The increased current in the series coils due to the heavy load, builds up the magnetism in the trailing tips *N* and *S* and maintains practically sparkless commutation at all loads. Thus we are enabled to operate, under load, at a higher armature speed and develop more power, while the shunt-winding limits the free speed to a safe figure.

A few years after the introduction of the d-c. drill, a-c. drills were developed. These were built to operate on 60 cycles and other prevailing frequencies such as

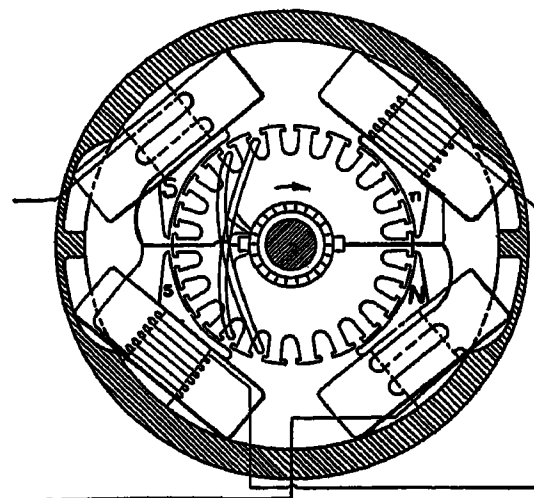


FIG. 1—COMPOUND-WOUND D-C. MOTOR

Special field structure

40 and 25 cycles. They, of course, had good speed regulation, but the weight, due to lower rotor speeds, being limited to 3600 rev. per min. at 60 cycles and correspondingly less for the lower frequencies, was somewhat of a drawback.

About 1908 the now well-known universal drill was introduced and has met with great favor on account of its ability to operate interchangeably at practically the same speeds on either direct or single-phase alternating current of a given voltage. The universal tool is series wound with the typical series motor speed regulation, however.

While the falling off in speed under load was considered to be of advantage in some classes of work, it has now been demonstrated that the sustained speed, as of the induction motor, is generally preferable, due

1. Elec. Engr., Chicago Pneumatic Tool Co., Cleveland, Ohio.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

to the accomplishment of a greater amount of work. This is particularly true of portable grinders as will be shown later.

It is quite obvious that the polyphase induction motor tool has distinct advantages over the direct current and universal tools both as regards speed regulation and lower maintenance cost, due to the absence of commutator and brushes as well as the insulated armature winding. One factor which has retarded its adoption, however, has been its greater weight due to the low rotor speed on commercial circuits of 60 cycles or less. All electric tools d-c., universal, and polyphase a-c. have always had the handicap of weight as compared with pneumatic tools, except at the sacrifice of sturdiness. Nevertheless, many users have put up with the greater weight of the electric tool, on account of the more convenient source of power supply.

In order to reduce the weight of the induction motor tool it is evident that we must bring the rotor speed up and we can do this only by increasing the frequency, since the 60-cycle drills were practically all provided with the minimum number of poles. The synchronous speed of a two-pole 60-cycle motor is 3600 rev. per min., whereas the d-c. and universal tool motors have free armature speeds of from 8000 to 16,000 rev. per min. and even higher in some of the smaller sizes. Under load these armatures slow down nearly 50 per cent which still leaves a speed higher than that of the 60-cycle motor.

HIGH-FREQUENCY TOOLS

A frequency of 180 cycles per second was adopted for the high-frequency portable tools, which gives a synchronous speed of 10,800 rev. per min. in the two-pole motor used. This is considerably less than the average free speed of the d-c. or universal tool which is very high. This means longer life for the bearings, which are generally of the ball type. The slip under normal full load is 8 per cent to 10 per cent, giving an average loaded speed of about 9800 rev. per min., which is much higher load than the speed of the d-c. or universal tool with its large speed drop. This, of course, means more power with a given size of rotor.

Several factors governed the selection of a standard frequency for these tools. Since it was necessary to obtain spindle speeds for the drills, reamers, and abrasive wheels which would conform to the modern cutting tools, there must be a point where the reduction in weight of the motor due to higher frequencies would be more than offset by the greater weight of the gearing required to obtain the necessary spindle speeds. From this point of view, the desirable frequency was found to be in the neighborhood of 180 cycles per second. Troubles in ball bearings and difficulty of lubrication at high speed is another limiting factor, although improvement in both directions indicates the possibility of still higher frequencies.

Thus the high-frequency tools meet the requirements

of intensified production in modern industry where portable tools are crowded to the utmost and in many cases get very little care. The outstanding advantages due to this application are:

- I. Greatly increased power for the same weight, due to the higher loaded speeds of the rotor.
- II. Reduced weight for a given power output.
- III. Practically constant speed at all loads (8 per cent to 10 per cent slip) which results in the accomplishment of more work.
- IV. Greatly reduced maintenance cost.

In order to give comparisons with other types, a concrete example of the increased power and better speed regulation of the high-frequency tool is shown in Fig. 2. Here, the actual watts input are plotted as the abscissas against b. hp. in curves No. 1 and 2 and against the spin-

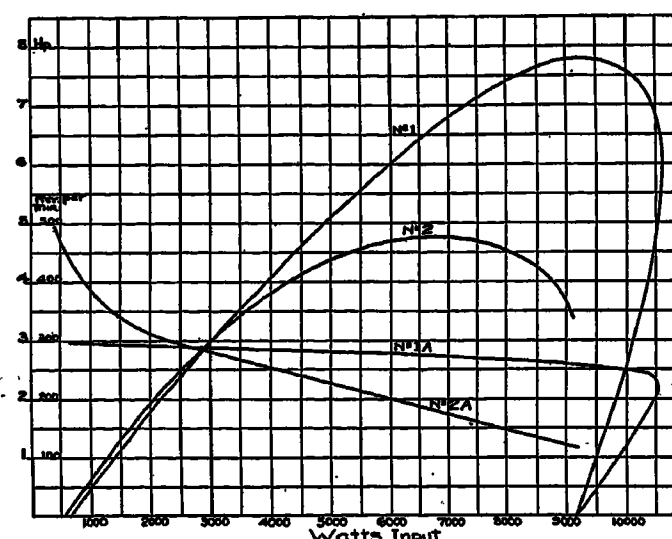


FIG. 2—COMPARISON OF HIGH-FREQUENCY AND D-C. REAMERS

Curve 1 is brake horsepower of high-frequency reamer
 Curve 2 is brake horsepower of d-c. reamer
 Curve 1A is speed of high-frequency reamer
 Curve 2A is speed of d-c. reamer

dle rev. per min. in curves 1A and 2A. Curves 1 and 1A show characteristics of a high-frequency reamer weighing 50 lb., while 2 and 2A are the corresponding curves of a d-c. reamer which weighs 68 lb. or 36 per cent more. The normal load rating of the high-frequency reamer is 5300 watts input at which point it develops 5.35 hp. at 280 spindle rev. per min., or with a slip of $6\frac{1}{2}$ per cent. The normal load rating of the d-c. reamer is 3600 watts at which point it develops 3.5 hp. and 265 rev. per min., representing a slip of $56\frac{1}{2}$ per cent. It will be noted that the reserve power above normal full load of the high-frequency tool is large as compared with the d-c. tool. The armature, exclusive of shaft and the ventilating fan, of the d-c. tool weighs $2\frac{1}{3}$ times as much as the high-frequency rotor.

Fig. 3 is the detail curve of the high-frequency reamer shown in the previous curve. Note the well sustained speed at maximum hp. and torque, the slip being 15 per cent, also the high-power factor.

A cast rotor of relatively low resistance is used in these tools, which gives close speed regulation. When they were first put on the market, it was thought that

the smaller tools should have considerable speed variation and a rotor wound with bare copper wire was used, making it possible to wind rotors of high or lower resistance as desired. While this practise has been discontinued in favor of the low-resistance cast rotor, it will be interesting to note what was accomplished,

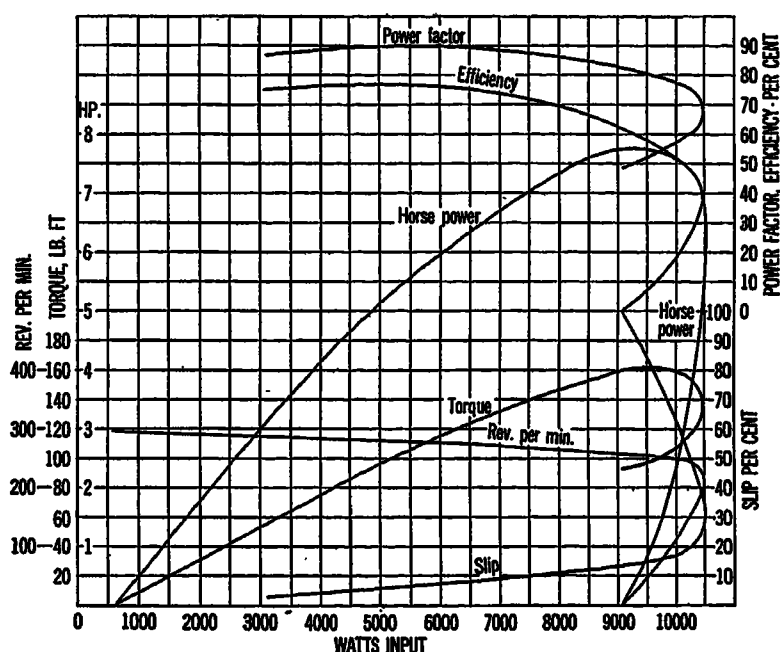


FIG. 3—CHARACTERISTICS OF LARGE HIGH-FREQUENCY REAMER

in the way of speed variation or slip in these small machines.

Fig. 4 shows the characteristic curves of a small drill weighing eight pounds and capable of drilling 5/16-in.

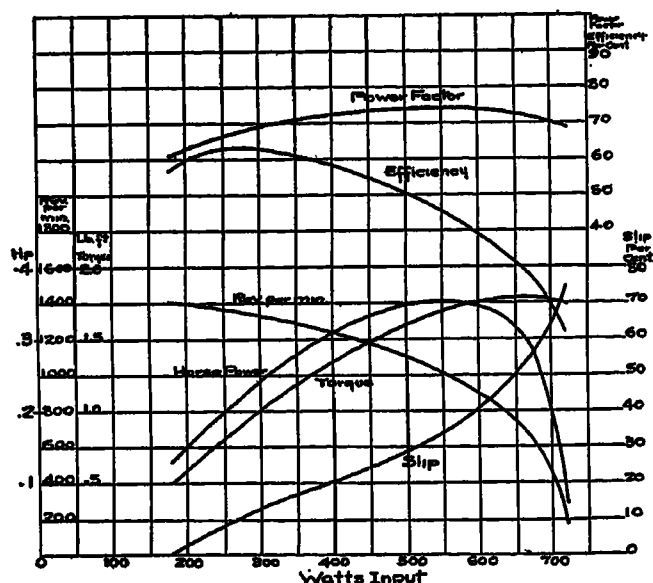


FIG. 4—CHARACTERISTICS OF SMALL HIGH-FREQUENCY DRILL WITH HIGH-RESISTANCE ROTOR

holes in steel. It has a high-resistance rotor. Note that a slip of 75 per cent was reached with the spindle torque very close to maximum. The maximum hp. was reached at about 30 per cent slip. With the low-resistance cast rotor, in the same stator, a slip of 31 per cent is obtained at the same watts input which gave a 75 per cent slip with the high-resistance rotor shown in Fig. 4, and the maximum hp. is developed at 8 per cent slip as against 30 per cent. The maximum hp. is also about 12 per cent greater with the cast rotor, these differences being due to the difference in rotor resistance.

Perhaps one of the most outstanding examples of the advantages of high-frequency tools is to be found in the portable grinder and buffer. Here the great advantage of sustained speed is very pronounced. The cutting wheel can be operated at the proper and most efficient speed without having to allow a high and dangerous free speed, as is the case with other types of electric and some air grinders. In addition to obtaining the most efficient cutting speeds for the wheels, the wheels themselves give practically double the life at the sustained speeds.

Fig. 5 shows the curves of four types of electric grinders, each having the same weight. The spindle, or arbor, rev. per min. are shown as the abscissas plotted against the hp.

Curve No. 1 is of a geared grinder with universal motor and the armature running about three times as fast as the spindle. Note the extremely high no-load speed of 5200 rev. per min., and the speed of 2000 rev. per min. at maximum hp.

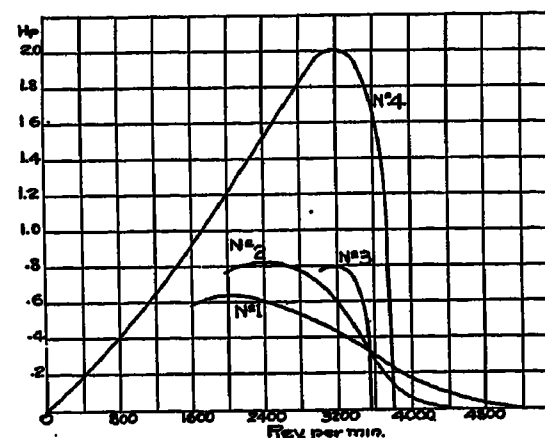


FIG. 5—COMPARISON OF ELECTRIC GRINDERS OF FOUR DIFFERENT TYPES

All these grinders have the same weight

- Curve 1—Geared universal-motor grinder
- Curve 2—Geared compound-wound d-c. grinder
- Curve 3—Gearless 60-cycle induction-motor grinder
- Curve 4—Geared high-frequency grinder

Curve No. 2 is of a geared compound-wound d-c. grinder. The effect of the shunt winding is made apparent in the reduced no-load speed. We also have a greater wheel speed at maximum hp.

Curve No. 3 is of a two-pole, 60-cycle induction motor grinder without gearing. The synchronous speed is 3600 rev. per min. Here we have good speed regulation and the absence of gearing is, of course, an advantage in that it permits of a larger motor for the same total weight of the tool.

Curve No. 4 is of a high-frequency grinder geared slightly less than three to one so that the free speed is about 3800 rev. per min. This has good speed regulation and very much more power due to the high rotor speed at full load. This is the only grinder of the group that will successfully carry a 6-in. abrasive wheel at proper speed and with sufficient power behind it. The rubber-bonded wheels which permit of a peripheral speed of 10,000 ft. per min. require a smaller gear ratio

thus increasing the arbor speed, or a larger diameter of wheel may be used with the same ratio.

A comparison of the high-frequency grinder with three types of pneumatic grinders is shown in Fig. 6. Here the arrangement of the curves is the same as in Fig. 5.

Curve No. 1 is of a reciprocating piston type of pneumatic grinder. Note the range of maximum power is at from 1400 to 2200 rev. per min., while the no-load speed is 4000.

Curve No. 2 is of a rotary pneumatic grinder. The load speed is 3000 to 3600 rev. per min., which is an improvement over No. 1, but the no-load speed is 6800 rev. per min., which is excessive for a 6-in. wheel.

Curve No. 3 is of a rotary pneumatic grinder provided with a throttling governor. Here the no-load speed is held down by throttling the air, not only making a safer tool but consuming less air at the lighter loads.

Curve No. 4 is of the same high-frequency grinder as was shown in Fig. 5. The speed is held within

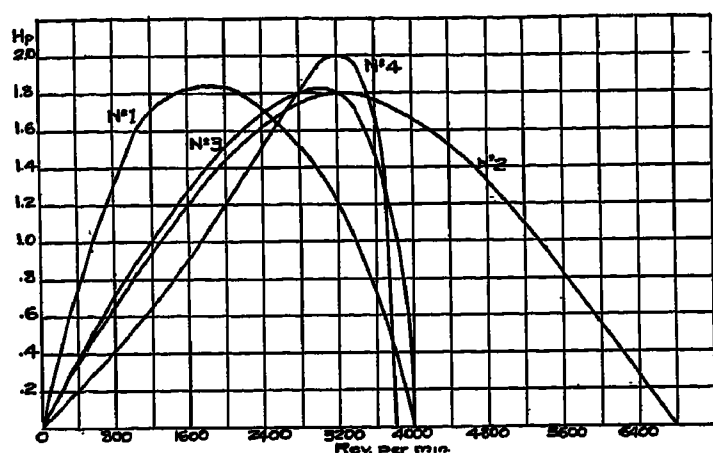


FIG. 6—COMPARISON OF PNEUMATIC GRINDERS WITH HIGH-FREQUENCY ELECTRIC GRINDER

Curve 1—Reciprocating pneumatic grinder
Curve 2—Rotary pneumatic grinder
Curve 3—Rotary pneumatic grinder with governor
Curve 4—Geared high-frequency grinder, same as in Fig. 5

close limits and there is plenty of power to handle the work. Furthermore, although not shown, the power consumption, as of all electric motors, is less at the lighter loads, while the converse is true of the pneumatic tools except in the case of the grinder in Curve No. 3.

Just as sustained correct speed makes for longer wear of grinding wheels and abrasive disks, so does it also give long life to reamers and drills. In reaming through a considerable thickness of steel when much metal is to be removed, a tool having great speed variation is apt to produce clogging of the reamer at extremely slow speeds and burning when the load is lessened with the reamer still in the hole.

A very striking example of the effect of nearly constant speed in increasing the life of the reamer was observed in a bridge fabricating plant with a 50-lb high-frequency tool having a synchronous speed of 300 rev. per min. The holes were punched 11/16 in. and reamed to 15/16 in. through assembled plates varying in group thickness from 1 1/4 in. to 3 3/4 in. Over 3000

linear in. of this reaming was done with one reamer without regrinding. This was at a reaming rate of 3.7 in. per min., including the time of changing from hole to hole.

As an example of reaming 15/16 in. full punched holes in deck plates, on ship work, a high-frequency reamer of 300 rev. per min. synchronous speed reamed 100 holes in 9 min., which was 39 per cent faster than with a compound-wound d-c. reamer weighing 40 per cent more.

In the drilling of metal it has been found that high-frequency drills selected as to proper speed for the size and nature of the holes to be drilled will do the work in one-half the time required by the d-c. or universal drills with their greater speed variation.

In the case of grinding of steel bars it was found that the high-frequency grinder removed 12 1/2 per cent more metal, over a period of several days, as compared with equal weight pneumatic grinders of the piston type. The d-c. and universal grinders as shown by the curves in Fig. 5 are not competitive with the high-frequency type.

So much more work can be accomplished with the high-frequency tool that large numbers of the older types of tools are being discarded. Manufacturers are recognizing the rapidly changing conditions and are willing to scrap the earlier tools to invest in the new equipment necessary, in the shape of frequency converters or motor-generator sets and new wiring in order to gain the advantages of the increased production. The cost of power is somewhat more due to the transformation to the high-frequency current, but the individual efficiency of the tools is higher than in the old types of tools. As the cost of current in many industries is only about one-twentieth of the cost of production labor, the great increase in productive capacity, made possible by the high-frequency tool, compensates many times for the slight increase in cost of current.

The outstanding advantages of high-frequency tools have been so apparent that new applications have been springing up with great rapidity. A few of the tool types and their applications will be described in the following paragraphs.

Fig. 7 shows a small tool equipped with a multiple jaw clutch held apart by means of a spring and put into engagement by means of pressure on the handle. When driving screws or running nuts, the torque developed at the end of the operation causes the abutting faces of the jaws to be forced apart, due to a very definite angle of contact between them.

Fig. 8 shows a nut runner for counterbalanced suspension, equipped with a cushion clutch which is adjustable for various sizes of nuts. This clutch which has multiple jaws, releases at a predetermined load and cannot drop into engagement again until the completion of one full revolution. The jaws are quite shallow and there is considerable angular clearance between the interlocking faces, so that when they drop

in, after having released, the driving faces come together with considerable speed and, due to the yielding effect of the spring which holds them together, they ride up and out of contact with practically no shock to the operator or tool.

Fig. 9 shows a large reamer weighing 50 lb. and

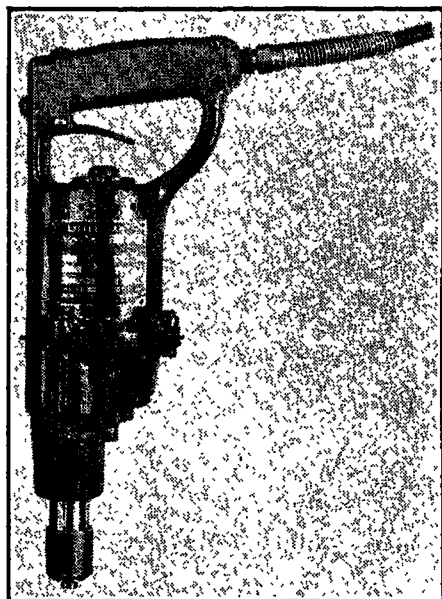


FIG. 7—HIGH-FREQUENCY SCREW DRIVER OR NUT RUNNER WITH POSITIVE CLUTCH

handled in most cases by two men. This is capable of $1 \frac{5}{16}$ -in. reaming in steel at a very rapid rate.

Fig. 10 shows a tool for driving screw studs and at the same time indicating their tightness. The tool is carried in a radial arm which is very flexible and serves to take the torque and support the weight of the tool.

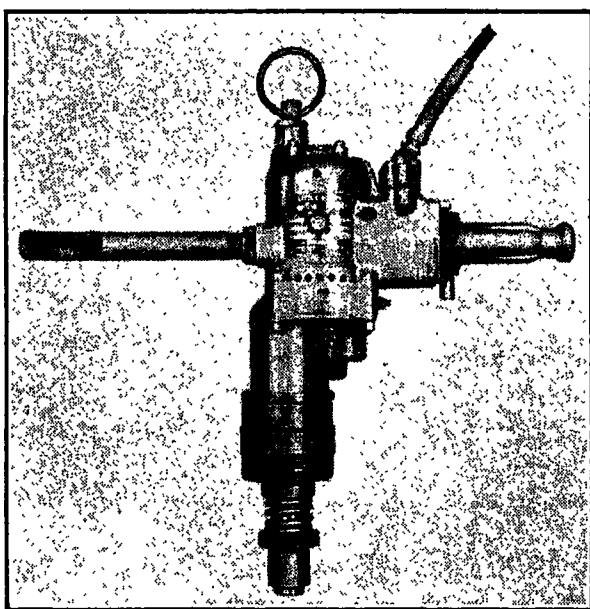


FIG. 8—HIGH-FREQUENCY NUT RUNNER WITH CUSHION CLUTCH

It has been the custom in putting in screw studs to drive them part way mechanically and then use a double ended wrench to feel them manually for tightness. This was a double operation and slow.

In the construction shown, the tool is free to turn on ball bearings, around its spindle axis, through an angle of 20 deg. or 30 deg., and this movement is resisted

by an adjustable weight and lever arm. A so-called solid chuck is generally used which screws over the upper end of the stud and the tool must be reversed to get it off after the stud is driven home. An automatic depth stop, set for the proper length of projection of the stud from the working surface, releases the driving clutch and stops the tool spindle. The raising of the hand lever at the right engages the reverse clutch and gearing in the tool.

After the tool starts to drive the stud in the tapped hole, the torque developed tends to turn the housing

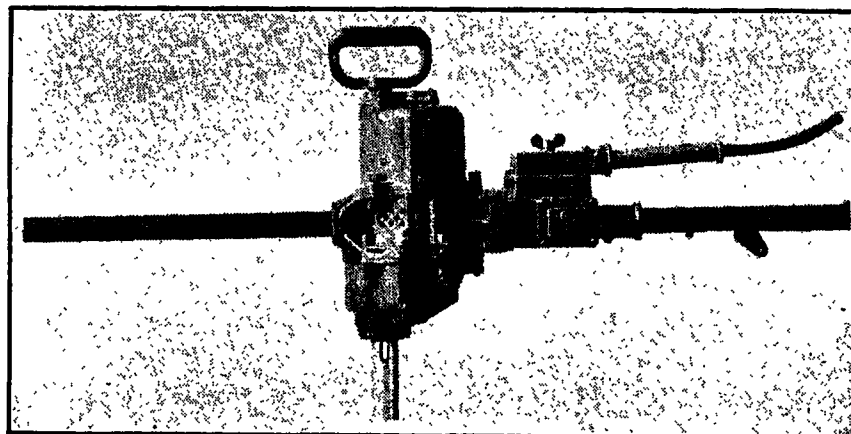


FIG. 9—HIGH-FREQUENCY REAMER
Capacity $1 \frac{5}{16}$ in., weight 50 lb.

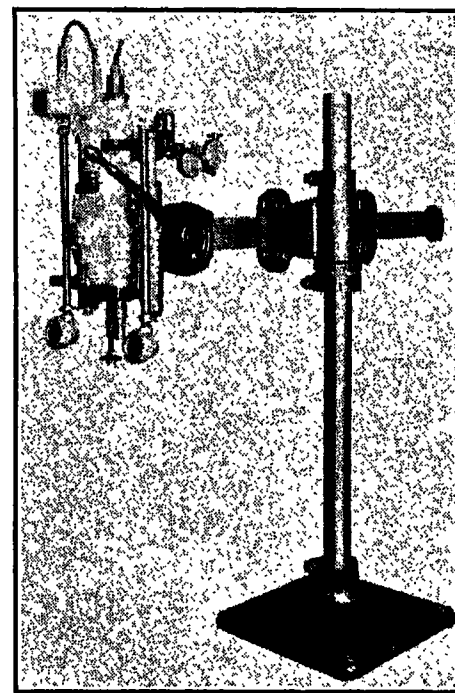


FIG. 10—HIGH-FREQUENCY STUD SETTER MOUNTED ON RADIAL ARM

of the tool against the weight and lever arm shown in Fig. 10 and if this torque is sufficient to lift the weight, an electrical contact is made which causes a green light to appear, indicating to the operator that the stud is of the proper tightness. In order to take care of the danger of getting studs too tight, as in cast iron, a second weight and lever are supplied, cooperating with a red light to indicate when the stud is going in too tightly. The excess torque causes the second weight to be lifted and the circuit for the red light to be completed. Current for the lamps is supplied through a small 4-volt transformer.

The radial arm shown in Fig. 10 is also used to carry nut runners as shown in Fig. 8. This relieves the operator of the weight and all shock of driving, even when the ordinary solid jaw clutch only, is used.

Fig. 11 is a typical portable grinder for foundry and general grinding.

Fig. 12 is a sander carrying a renewable abrasive disk for the sanding of automobile bodies and similar work.

There are many other tool applications which are

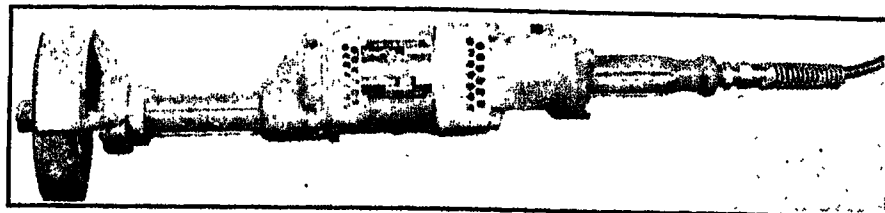


FIG. 11—HIGH-FREQUENCY GRINDER

Wheel 6 in. by 1 1/2 in.

modifications of those shown. Eight motor sizes comprise the group of tools, Fig. 7 to Fig. 12, with a large number of gear ratios and mechanical combinations.

SUPPLYING THE HIGH-FREQUENCY ENERGY

There are two well known methods of transforming commercial current to high frequency current, *viz.* the frequency converter and the motor-generator.

The frequency-converter can be used only when the primary current is alternating. As generally employed for operating high-frequency tools it consists of special windings in a slip-ring motor frame, the rotor of which is driven backward, usually by an induction or synchronous motor. In operating high-frequency tools, it has been customary, with a 60-cycle source of supply, to employ an 8-pole frequency converter, driven at 1800 rev. per min. to furnish 180 cycles. The stator winding is excited with 60-cycle energy and the supply line for the tools is connected to the slip-rings. The field produced in the stator winding rotates in one direction at 900 rev. per min. The rotor is turned in the opposite direction at 1800 rev. per min. giving a net speed of 2700 rev. per min. which gives 180 cycles in the eight-pole rotor. As satisfactory tool operation depends on good voltage regulation, it has been the aim of the manufacturers to hold within 8 per cent voltage variation, the full-load voltage being 220. The frequency converter has an inherent regulation and the voltage at a given load varies only with the primary voltage.

The motor-generator or alternator provides an entirely new current, and at 1800 rev. per min., a 12-pole generator will be required to produce 180 cycles. The motor can be operated from either d-c. or a-c. If the latter, an exciter will be required for the generator fields. A regulation not to exceed 8 per cent is also desired with this set but it is possible to vary the

voltage either manually or automatically by changing the field current of the generator.

Each type has its advantages and while the simplicity of the frequency converter appeals to many, the possibility of voltage regulation seems more important to others.

The current used for high-frequency tools is three-phase and a cable with four conductors is provided with the tool, terminating in a suitable plug. The fourth conductor is grounded to the housing of the tool and the receptacle in the power line is grounded. This seems to have been satisfactory in the prevention of shocks from grounded windings. It has been suggested that a fourth collector ring be provided on the frequency converter or motor generator to connect to the neutral of the star connected windings and to ground.

Many ways of bringing current to the tools have been devised. The 4-point plug and cable method has been the most popular. Another method, recently offered, consists of four bare copper wires used as trolley wires in an insulated trough or enclosure. These are suspended over the work and a four wheel trolley brings current through a short cable to the tool. The fourth

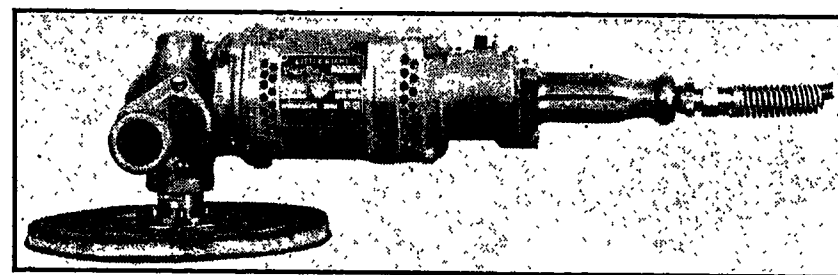


FIG. 12—HIGH-FREQUENCY SANDER

Carrying 9-in. abrasive disk

trolley wheel and wire is of course for grounding purposes.

Much hard work was done in pioneering the high-frequency tool, as long tests had to be made to convince the manufacturers of its ability to stand up under the rigorous duty which it seemed capable of performing. It has withstood these tests over a period of several years and those who are familiar with its capabilities cannot help but feel that the high-frequency tool represents the greatest advance made in portable tools since their introduction.

Discussion

A. M. MacCutcheon: I was greatly impressed by Mr. Coates' statement that they get 5.35 hp. out of 50 lb. of material, including the mechanical parts of the tool.

I was particularly interested in Mr. Coates' comments on the source of power. He mentioned that good regulation was very desirable. In that connection, some experiments have been made with a source of high-frequency energy which has come back into use recently because of a demand for very excellent regulation.

The machine might be described as a rotating transformer where alternating current is fed into the rotating member through sliprings and alternating current is taken out through a com-

mutator. If the machine is stationary, it is obvious that the frequency that is fed in is the same as the frequency that comes out. If the machine is operated by an outside source of power at the same speed, that is, the speed which would correspond with the synchronous speed of the winding, direct current is obtained. If 60-cycle energy is fed in and the machine is driven backward, the frequency will be doubled.

This type of machine may be driven by an induction motor. If the winding is a 6-pole winding, with synchronous speed of 1200, but is operated at 900, 15 cycles will be secured.

I have wondered whether there would be a demand for a higher frequency than the 180-cycle.

The regulation of this machine, which may be described as a rotating transformer, is very excellent, at least at low frequency, where I have the tests in mind. Regulation as good as 3 per cent has been obtained on 15-cycle alternation.

I hope that in the A. I. E. E. TRANSACTIONS more and more papers will appear on the application of electricity. I recall that in our own factory about six or seven years ago, although it is a factory manufacturing electrical equipment, air tools were used. In the last five years that has been entirely changed and no air tools are found, they are all electrical.

J. H. Snyder: The induction frequency changer has an advantage over the motor-generator frequency changer in that the motor driving the generator need not have the same capacity as the generator. For instance, in stepping up from 60 cycles to 180 cycles, the generator will provide one-third of the energy through its primary winding and two-thirds of the energy will have to be provided through the driving motor.

That feature of the induction frequency changer makes it in a great many cases less expensive in first cost than the motor generator.

Referring to the regulation of the induction frequency changer, Mr. Coates, I believe, stated that usually a regulation of 8 per cent is specified. That regulation is very good and is not detrimental to the motor when the frequency changer is operated at very high loads.

The commercial motors are at the present time guaranteed for 10 per cent overload and, therefore, if you have any regulation, you are well within the 10 per cent guarantee, so there is no damage possible by operating the high-frequency tool at slightly higher than the rated voltage.

The regulation of a motor-generator type of machine is inherently poorer than that of the induction type of machine; however, as Mr. Coates pointed out, the voltage can be varied by changing the field of the generator to any value desired. This requires expensive automatic apparatus or else an operator.

There is also the question of low power factor in connection with the induction frequency changer, but the amount of power used by the high-frequency tool is usually very small compared to the total amount of power used so that the power factor of the total load is not greatly lowered.

Where large numbers of high-frequency tools are employed the power factor may be raised by the use of capacitors connected to the line.

The present voltage seems to be 220 but there is some demand for an even lower voltage such as 110. Transmitting 110 volts at 180 cycles is quite a problem, if the distribution system is long. It has been suggested that the power be generated at 440 volts or higher and transformed at various points and used at 110 volts. That would have the advantage of using 110 volts on the tool and still transmitting at a higher voltage. The transformer involved in such a case would not be very large. It is, of course, well known that the transmission of power by means of compressed air is very inefficient and I believe that the 180-cycle tool has a higher over-all efficiency than the pneumatic. Also, the maintenance on air lines and hose connections, etc., is rather high.

B. B. Ramey: The portable electric tool moved along rather slowly while we had only the slow-speed motors which made the

tools so bulky, but with the introduction of the universal motor, when the size was much reduced because of high speed, the development became very rapid. Now the 180-cycle tool has come in to speed up production still further. That point which Mr. Coates brings out in regard to speeds being maintained is the point around which the greater production and lower cost revolve.

In regard to the universal tool as compared with air, my impression is that the universal tool is not as much handicapped as Mr. Coates' statements seem to indicate. It is my feeling that the universal-motor tool is superior to the air tool in general applications, with the exception of air riveters.

The high-frequency tool is going into industrial plants and taking the place of air equipment rather rapidly, because it can stand up under the heaviest class of service and produce as much work as the air tool, in fact even more. The high-frequency tool is much lower in weight than any other tool.

The ventilation of the high-frequency tool is much better than on the universal tool wherein the speed drops off very rapidly under the heavy loads and the ventilation is greatly reduced.

In regard to the frequency of 180-cycles, I think another fact that accounts for its adoption is that it gives about the best frequency combination that can be got from the standard frequencies of 50 and 60 cycles. Two hundred cycles or higher would give greater motor capacity, but in some cases would involve more expensive gearing to reduce to proper tool speeds. The system of frequency changers, which Mr. MacCutcheon mentioned, is very interesting and I hope something can be developed along that line to help further the use of portable electric tools. My thought is that in order to get the benefits of the high-frequency tool to the small user of portable tools, it will be necessary for this high frequency to be supplied by the power companies.

I believe the loss in the line at 180 cycles amounts to very little in lines less than $\frac{1}{2}$ in. in diameter. Of course, in supplying the power in large quantities so the conductor is very large for 110 volts, it may be necessary to transmit it at the higher voltage and then transform it down.

C. B. Coates: I saw the rotary converter which Mr. MacCutcheon described and it looks as though it has great possibilities. It is very flexible and no doubt can be applied to the driving of high-frequency tools.

In regard to raising the voltage for transmission purposes which Mr. Snyder spoke of, this has not been found necessary, because in the larger installations, sometimes involving as many as 1000 tools, it has been customary to install several frequency converters around the plant in order to economize on wiring. The largest units installed so far are 75 kv-a. The reactance is, of course, three times what it would be for 60 cycles, but by proper arrangement of the wires and wiring the reactance voltage can be kept down to a small value in the 220-volt transmission.

Mr. Ramey's suggestion that there might be a possibility of the power companies supplying high-frequency current for portable tools is very interesting and I am sure this would be welcomed by the manufacturers of such tools.

The tendency has been to install frequency converters or motor-generator sets having excess capacity for the immediate work involved so that there will be ample capacity for future additions. In one of the very early installations in an automobile body plant, a 12-kv-a. motor-generator set was installed to operate 20 tools. It was found later that, owing to the extremely low load (diversity) factor, it was possible to have 60 tools connected to this set. The low load factor was due largely to the great rapidity with which the work was accomplished as compared with the old methods. It has been found practical to install as few as six tools in a plant, in view of the lower maintenance cost and the greatly increased production. Of the installations now in operation about 60 per cent are operated by frequency converters and 40 per cent by motor-generator sets.

Electric Heating Elements

Some Fundamentals Used in Their Design

BY EDWIN FLEISCHMANN*

Member, A. I. E. E.

Synopsis.—The paper presents the derivation from elementary principles of equations for the design of heating elements. These are then connected with Stefan's law of radiation, and also with a

much-used rating curve which has given good results. The reason for the conservatism of this latter curve is shown, and a numerical example worked out for both the theoretical and empirical curves.

INTRODUCTORY

THE classical basis, upon which the theory of electric heating design rests, need only be suggested. It is founded on several well-known electrical and thermal laws,—for example, those of Ohm, Wien, and Planck, and the familiar Stefan-Boltzman equation. To be sure, certain data which are based solely upon fortuitous experiment have been useful; but the fundamental relationships must not be ignored. It is the purpose of the present paper to outline briefly some principles in the use of electricity for heat, pointing out particularly those basic ones which govern its skilful employment.

Attention will be focused primarily upon the three vital factors of design and their relation to each other in industrial heating work: the laws of Ohm, the equation of Stefan-Boltzman, and the limitations which govern their use with the materials available for heating elements. The first two canons are more or less well-founded upon theory; the last is substantiated only by experience, but is none the less important at the present stage of the art.

In this paper attention is confined to metallic resistors for high-temperature work (up to 1850 deg. fahr.). It is here that the upper safe value of the operating temperature of the heating unit is approached. At lower temperatures, of course, only part of the heat generated in the elements is carried away by radiation, there being some conduction and considerable convection. At 1850 deg. fahr., the losses by radiation in air are about 90 per cent of the total. In a sealed enclosure, such as a furnace chamber may often be assumed to represent, the heat is all black-body radiation. It is interesting to note that this fact was arrived at simultaneously by Kirchhoff and Balfour Stewart, about 1858. Hence, Ohm's Law and the Stefan-Boltzman Equation together connect electricity and heat completely.

MATERIAL FOR HEATING ELEMENTS

For temperatures up to 1850 deg. fahr., there is really only one material from which a practical life can be obtained. This is an alloy containing normally

about 80 per cent nickel and 20 per cent chromium, with practically no iron. The susceptibility of iron to oxidation endangers the life of the metal at elevated temperatures; so that in the best metals it is carefully avoided. The alloy has the property of forming upon its surface a complicated metallic layer, of which the metallography is still not clearly understood. It is known, however, that this coating effectively prevents further oxidation of the body of the material below 2100 deg. fahr. (1150 deg. cent.). Thus, it assures the life of the element at ordinary heat-treating temperatures.

The resistivity of nickel chromium is consistent and fairly uniform, as indicated by the curves in Fig. 1. Data have been taken from two of the manufacturers'

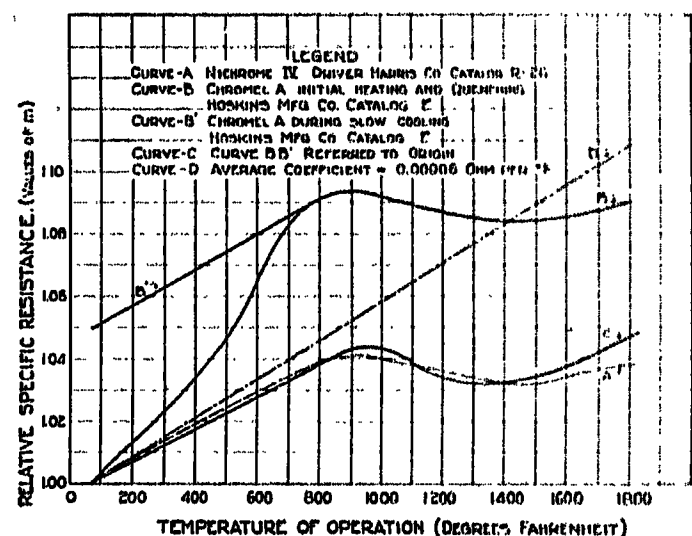


FIG. 1—RESISTANCE OF NICKEL-CHROMIUM AT ELEVATED TEMPERATURES

catalogs, for material of substantially the same composition. It should be observed that the initial heating and quick cooling of the material give a rise of almost 12 per cent in resistance between cold and 1850 deg. fahr. However, the conditions in a furnace chamber more nearly resemble annealing, since the resistor is seldom cooled very quickly. All the curves are plotted for relative resistances, assuming a specimen of one ohm resistance at 68 deg. fahr. (20 deg. cent.). This material proves to be a satisfactory one for heating units, and it is widely used.

Electric heat is developed in, and by virtue of the properties of the heating element itself, without regard to any extraneous agency, except the supply of electric current. Provision must, therefore, be made for

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sufficient radiating surface on the unit, wherefrom the heat generated in it may be dissipated. It is almost axiomatic that a body to which heat is being supplied will rise in temperature until the losses from its surface just balance the input, provided, of course, that there are no other abstractions of heat from or within the body. Not only must the required amount of heat be generated in the element, but the heat must also be utilized in such a way that the surface temperature of the unit itself will never exceed 2100 deg. fahr. These seemingly elementary facts are the bases of all industrial heating design.

OHM'S LAW

The familiar law of Ohm states that

$$E = I R \quad (1)$$

where I = the current in amperes,
 E = the impressed voltage, and
 R = the resistance in ohms.

The power in watts is the product of E and I , or

$$E I = I^2 R \quad (2)$$

The power may also be expressed in B. t. u., or calories, by application of suitable conversion factors. One watt is equivalent to 3.412 B. t. u. per hour; or one kilogram-calorie per hour equals 1.162 watts. $E I$ is the heating effect of the current.

A variant form of Equation (2) may be obtained by substituting for I its value E/R from (1):

$$E I = \frac{E^2}{R} \quad (3)$$

This gives the heating effect in terms of the voltage and resistance. Both relationships will be found useful in the later stages of the discussion.

The general expression for resistance of a conductor at any temperature is

$$R = m \rho \frac{L}{A} \quad (4)$$

where

R is the resistance in ohms,

m is a constant for any given temperature expressing the ratio of the resistivity at that temperature to the resistivity at some temperature of reference. For nickel chromium, the values of m are shown in Fig. 1.

ρ is the specific resistance, or resistivity at the temperature of reference. In the case of nickel chromium, the value of ρ is 625 ohms per cir-mil-ft., or 0.00004091 ohms per in. of length per sq. in. of cross-sectional area. The latter figure will be used hereafter, because we shall define

L as the length in in., and

A as the cross-sectional area in sq. in.

Substituting the value of ρ in (4), there results for nickel chromium

$$R = \frac{0.00004091 m L}{A} \quad (5)$$

If, now, this value of R be substituted in Equations (2) and (3), they become

$$E I = \frac{I^2 m \rho L}{A} \quad (6)$$

$$E I = \frac{0.00004091 I^2 m L}{A} \quad (7)$$

$$\text{and, } E I = \frac{E^2 A}{m \rho L} \quad (8)$$

$$E I = \frac{24444 E^2 A}{m L} \quad (9)$$

Here are expressions for the wattage generated in a nickel chromium resistor in terms of the voltage, or current, and the physical properties and dimensions of the piece.

Extensions of the theory are now in order. There are several types of resistor cross-sections in fairly general use today. Of these, the most susceptible of mathematical treatment are the round rod and flat ribbon. It will be interesting to consider these shapes in parallel columns. No effort will be made to point out or explain the superiority of one over the other; for, so far as can be determined experimentally, or theoretically, the differences are more hypothetical than actual. Rather will an effort be made to assist the engineer who employs either type in his work to do so intelligently, in the light of fundamental facts.

There is no difficulty in applying the laws to other shapes. The Equations already derived, (4), (6), and (8), are perfectly general. The geometrical simplicity of the rectangular and circular cross section recommends them for this elementary discussion.

The cross-sectional areas in the two cases will be:

Round Rod

Flat Ribbon

$$A = \frac{1}{4} \pi D^2 \quad (10a) \quad A = a b \quad (10b)$$

where D is the diameter of the rod in in.

where a is the width of the ribbon in in., and b is the thickness of the ribbon in in.

Putting these values in Equations (6) and (7), one obtains for:

Round Rod

Flat Ribbon

$$E I = \frac{4 m \rho I^2 L}{\pi D^2} \quad (11a) \quad E I = \frac{I^2 m \rho L}{a b} \quad (11b)$$

or, for nickel chromium,

$$E I = \frac{0.0000521 m I^2 L}{D^2} \quad (12a) \quad E I = \frac{0.00004091 m I^2 L}{a b} \quad (12b)$$

And if these values be substituted in (8) and (9), the following result:

<i>Round Rod</i>	<i>Flat Ribbon</i>
$E I = \frac{\pi E^2 D^2}{4 m \rho L} \quad (13a)$	$E I = \frac{E^2 a b}{m \rho L} \quad (13b)$
$E I = \frac{19195 E^2 D^2}{m L} \quad (14a)$	$E I = \frac{24444 E^2 a b}{m L} \quad (14b)$

There are no exceptions to these rules, which show exactly how heat is generated in these two shapes. They are fundamental.

Having determined the manner in which the heat is developed, we may next examine the means whereby it can leave the element; for it is of no value to do useful work unless it reaches the material to be heated. The only way in which heat can leave the unit is through the peripheral surface. The density with which it passes through,—i. e., the wattage radiated or lost by any means from the periphery per square inch, in the terms already used,—will determine precisely the temperature to which the resistor will rise above its surroundings.

The wattage per sq. in. can be related to the physical dimensions of the heating unit itself. If the peripheral surface of the resistor be denoted by S ,

<i>Round Rod</i>	<i>Flat Ribbon</i>
$S = \pi D L \quad (15a)$	$S = 2(a + b) L \quad (15b)$

The wattage per sq. in. of surface will, then, be $E I/S$. For convenience, set

$$G = E I/S \quad (16)$$

Then, using this value, and, for

<i>Round Rod</i>	<i>Flat Ribbon</i>
dividing (11a) and (12a) by (15a),	dividing (11b) and (12b) by (15b),
$G = \frac{4 I^2 \rho m}{\pi^2 D^3} \quad (17a)$	$G = \frac{I^2 \rho m}{2 a b (a + b)} \quad (17b)$
$G = \frac{0.00001658 I^2 m}{D^3} \quad (18a)$	$G = \frac{0.00002045 I^2 m}{a b (a + b)} \quad (18b)$

And, in a similar manner, dividing (13a) and (14a) by (15a),

$G = \frac{E^2 D}{4 m \rho L^2} \quad (19a)$	dividing (13b) and (14b) by (15b),
$G = \frac{6111 E^2 D}{m L^2} \quad (20a)$	$G = \frac{E^2 a b}{2 m \rho L^2 (a + b)} \quad (19b)$
$G = \frac{6111 E^2 D}{m L^2} \quad (20a)$	$G = \frac{12222 E^2 a b}{m L^2 (a + b)} \quad (20b)$

These equations go still further and give the number of watts per sq. in. which it is possible to lose from

the given shapes of resistors, in terms of their physical dimensions, and either the voltage applied to them, or the current flowing in them. They are extremely useful in design work.

Several simple transformations suggest themselves. One is often interested in the current density in the conductor. The density

$$Q = I/A \quad (21)$$

whence, for

<i>Round Rod</i>	<i>Flat Ribbon</i>
$Q = \frac{4 I}{\pi D^2} \quad (22a)$	$Q = \frac{I}{a b} \quad (22b)$

and,

$I = \frac{\pi}{4} Q D^2 \quad (23a)$	$I = Q a b \quad (23b)$
---------------------------------------	-------------------------

Substituting this value in (17a) and (18a)

$G = \frac{1}{4} Q^2 \rho D m \quad (24a)$	$G = \frac{Q^2 m \rho a b}{2(a + b)} \quad (24b)$
--	---

$G = 0.000010225 Q^2 D m \quad (25a)$	$G = \frac{0.00002045 Q^2 m a b}{a + b} \quad (25b)$
---------------------------------------	--

In short, the wattage per sq. in. of the surface varies with the square of the current density, for any given cross-section.

The voltage per unit length may also be of importance, in its relation to the wattage per sq. in. of surface. This appears very easily from Equation (19). Setting F equal to the voltage per in. of length, and F' equal to the voltage per ft. of length,

$$F = E/L \quad (26)$$

$$F' = \frac{12 E}{L} \quad (27)$$

Since E^2/L^2 appears in both Equations (19) and (20), the substitution will yield,

<i>Round Rod</i>	<i>Flat Ribbon</i>
$G = \frac{F^2 D}{4 \rho m} \quad (28a)$	$G = \frac{F^2 a b}{2 m \rho (a + b)} \quad (28b)$

$G = \frac{6111 F^2 D}{m} \quad (29a)$	$G = \frac{12222 a b F^2}{m (a + b)} \quad (29b)$
--	---

Or, from (27),

$G = \frac{F'^2 D}{576 \rho m} \quad (30a)$	$G = \frac{F'^2 a b}{288 m \rho (a + b)} \quad (30b)$
---	---

$G = \frac{42.43 D F'^2}{m} \quad (31a)$	$G = \frac{84.86 a b F'^2}{m (a + b)} \quad (31b)$
--	--

STEFAN-BOLTZMAN LAW

The Stefan-Boltzman equation is an hypothesis guessed at by Stefan¹ in 1879 as a result of one of Tyndall's experiments, and conclusively proved by Boltzman² mathematically in 1884, being substantiated by many subsequent investigations. It states that the total radiation from a body is proportional to the fourth power of its absolute temperature:

$$R = K T^4 \quad (32)$$

where

R is the total radiation per unit of surface in fundamental units;

T is the absolute temperature on the Kelvin scale; and
 K is the constant of proportionality.

the *Smithsonian Physical Tables*. This value has been used throughout the present paper.

For any combination of temperatures, using nickel chromium resistors,

$$G = 3.169 \left[\left(\frac{T_1 + 459.4}{1000} \right)^4 - \left(\frac{T_0 + 459.4}{1000} \right)^4 \right] \quad (34)$$

This equation expresses the total possible exchange of radiation between resistor and charge, under the temperature conditions stated, with the heated body running unmuffled in the furnace chamber, and takes into account the emissivity of the heater material, which is slightly less than that of a black body.

Frequently, however, the full effect of the radiating

TABLE I

Authority	Value given	Units	$K' = \text{value in watts/sq.in./deg. fahr.}^4 \times 10^{12}$
<i>Smithsonian Physical Tables</i>	5.72×10^{-12}	Watts/cm ² /deg. cent. ⁴	3.521
Goodenough ⁵	0.1618×10^{-8}	B. t. u./sq. ft./deg. fahr. ⁴ /hr.	3.293
Kimball ⁶	1.3×10^{-12}	g. cal./cm ² /deg. cent. ⁴ /sec.	3.335
<i>Standard Handbook for Electrical Engineers</i> ⁷	5.7×10^{-12}	Watts/cm ² /deg. cent. ⁴	3.506
Kurlbaum ⁸	5.32×10^{-12}	Watts/cm ² /deg. cent. ⁴	3.264
Woodson ⁹	1700×10^{-12}	B. t. u./sq. ft./deg. fahr. ⁴ /hr.	3.459

The equation is not very useful in this form, since the total radiation is scarcely ever of much import. Rather is the exchange of heat between hot and cold bodies, or between resistor and charge, in the furnace chamber, of interest. R may, therefore, be expressed in watts per sq. in. of radiating surface, and

$$G = K' e \left[\left(\frac{T_1 + 459.4}{1000} \right)^4 - \left(\frac{T_0 + 459.4}{1000} \right)^4 \right] \quad (33)$$

wherein

K' is the constant of proportionality;

e is the relative emissivity of the radiating material.

For black bodies, $e = 1.00$; for nickel chromuim, $e = 0.9$;

T_1 is the temperature of the resistor in deg. fahr.; and
 T_0 is the temperature of the furnace chamber in deg. fahr.

The values of K' are variously given by present-day authorities. The divergence of the figures is indicated by those cited in Table I. An extensive study of all available data on this constant has been made by the Bureau of Standards.³ The best agreement seems to be upon the figure given by Coblentz,⁴ and included in

1. *Sitzungsberichte der Königlichten Gesellschaft der Wissenschaften zu Wien*, Band LXXIX, p. 391, 1879.

2. *Annalen der Physik*, Band XXII, pp. 31 and 291, 1884. This proof is given in English in simple form in *Theory of Heat*, by Thomas Preston, 3rd Ed., p. 566. It is based upon thermodynamics and the electromagnetic theory of light. Since its appearance, the so-called Wein-Planck law has appeared (*Vorlesungen über Warmestralung*, partially reprinted in *Encyklopädie der Mathematischen Wissenschaften*, Band V-3, Heft 2, 1909) and the Stefan Law is also deducible with relative simplicity from this equation, which gives the distribution of radiation in the spectrum by relating it to wavelength, and absolute temperature.

periphery is not obtained. Proximity of walls or charge, or adjacent strands of the element exercise a blanketing effect, which reduces the liberation of heat at any given temperature.¹⁰ Where the efficiency of radiation is less than 100 per cent, under such conditions as those described by Keene and Luke, Fig. 2 defines the limiting allowable conditions for design of nickel chromium units. It is based upon a maximum allowable element temperature of 2100 deg. fahr. To insure long life of the heaters, their rating must fall below the curve which represents the condition of size, spacing, and radiating efficiency (C) under consideration.

The curves of Fig. 2 apply only to the heat lost by radiation; but that they may be safely employed to indicate the permissible total losses from the element is shown by the dotted curve, which gives the loss of heat from a body at 2100 deg. fahr. by both radiation and convection. Rice¹¹ has shown that the convection

3. U. S. Department of Commerce, Bureau of Standards, Scientific Paper No. 406, entitled *Present Status of the Constants and Verification of the Laws of Thermal Radiation of a Uniformly Heated Inclosure*, by W. W. Coblentz, December 20, 1920.

4. *Proceedings of the National Academy of Science*, Vol. 3, p. 504, 1917.

5. *Mechanical Engineers' Handbook*, 2nd Ed., p. 317.

6. *College Physics*, 2nd Ed., p. 317.

7. Fifth edition, p. 204.

8. Quoted in Preston, *Theory of Heat*, 3rd Ed., p. 564. Later work (1912) gives a value of K' of 3.335. See note 6.

9. A. I. E. E. JOURNAL, December, 1925, p. 1354.

10. A discussion of the relative efficiency of several arrangements of heating units may be found in *Rating of Heating Elements for Electric Furnaces*, by A. D. Keene and G. E. Luke, A. I. E. E. TRANSACTIONS, Vol. XLV, 1926, p. 475.

11. A. I. E. E. TRANSACTIONS, Part I, Vol. XLII, 1923, p. 653; Part II, Vol. XLIII, 1924, p. 131.

loss in still air is

$$G' = K'' (T_1 - T_0)^{5/4} \quad (35)$$

where T_1 and T_0 are the temperatures of the resistor and chamber respectively, in deg. fahr. An average value of K'' for nickel chromium may be taken from those determined by Keene and Luke to be approximately 0.0010795, although this evidently varies widely for different shapes of resistor.

The total losses, upon which the dotted curve of Fig. 2 is based, would then be the sum of Equations (34) and (35):

$$G + G' = 3.169 \left[\left(\frac{T_1 + 459.4}{1000} \right)^4 - \left(\frac{T_0 + 459.4}{1000} \right)^4 \right] + 0.0010795 (T_1 - T_0)^{5/4} \quad (36)$$

It will be seen that when the limiting curves given embody radiation only, a small factor of safety is obtained. They may, therefore, be used with confidence.

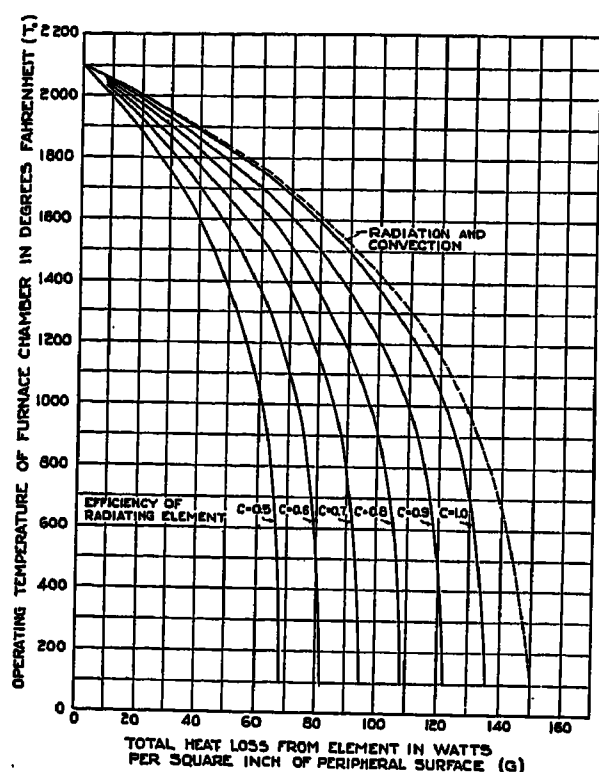


FIG. 2—THEORETICAL RADIATION FROM NICKEL-CHROMIUM RESISTOR OPERATING AT 2100 DEG. FAHR.

COMBINATIONS OF THE TWO LAWS

It is at once evident that in designing resistors, both of the laws must be heeded; and some very useful relationships can be adduced, by substituting the values of G found in Equations (17), (18), (19), (20), (24), (25), (28), (29), (30), and (31) in Equation (34). For this purpose, set $T_1 = 2100$ deg. fahr., in Equation (34), and write

$$G_0 = 3.169 C \left[42.85 - \left(\frac{T_0 + 459.4}{1000} \right)^4 \right] \quad (37)$$

in which C is the radiating efficiency already defined, as shown in Fig. 2. Then from (17) and (18),

<u>Round Rod</u>	<u>Flat Ribbon</u>
$D = 0.7401 \sqrt[3]{\frac{I^2 \rho m}{G_0}} \quad (38a)$	$ab(a+b) = 0.5 \frac{I^2 \rho m}{G_0} \quad (38b)$

$$D = 0.0255 \sqrt[3]{\frac{I^2 m}{G_0}} \quad ab(a+b) \quad (39a)$$

$$= 0.00002045 \frac{I^2 m}{G_0} \quad (39b)$$

Similarly, from (19) and (20)

<u>Round Rod</u>	<u>Flat Ribbon</u>
$D = \frac{4 m \rho G_0 L^2}{E^2} \quad (40a)$	$\frac{ab}{a+b} = \frac{2 m \rho L^2 G_0}{E^2} \quad (40b)$
$D = \frac{0.0001637 m G_0 L^2}{E^2} \quad (41a)$	$\frac{ab}{a+b} = \frac{0.0000818 m L^2 G_0}{E^2} \quad (41b)$

From (24) and (25)

<u>Round Rod</u>	<u>Flat Ribbon</u>
$D = \frac{4 G_0}{Q^2 m \rho} \quad (42a)$	$\frac{ab}{a+b} = \frac{2 G_0}{Q^2 m \rho} \quad (42b)$
$D = \frac{97,800 G_0}{Q^2 m} \quad (43a)$	$\frac{ab}{a+b} = \frac{48,890 G_0}{Q^2 m} \quad (43b)$

Equations (28) to (31) inclusive give

<u>Round Rod</u>	<u>Flat Ribbon</u>
$D = \frac{4 m \rho G_0}{F^2} \quad (44a)$	$\frac{ab}{a+b} = \frac{2 m \rho G_0}{F^2} \quad (44b)$
$D = \frac{0.0001637 m G_0}{F^2} \quad (45a)$	$\frac{ab}{a+b} = \frac{0.0000818 m G_0}{F^2} \quad (45b)$
$D = \frac{576 m \rho G_0}{F'^2} \quad (46a)$	$\frac{ab}{a+b} = \frac{288 m \rho G_0}{F'^2} \quad (46b)$
$D = \frac{0.02358 m G_0}{F'^2} \quad (47a)$	$\frac{ab}{a+b} = \frac{0.01179 m G_0}{F'^2} \quad (47b)$

The values of G_0 for any temperature and radiating efficiency may be taken directly from Fig. 2. To facilitate calculations involving flat ribbon, Table II may be used. It gives values of a , b , ab , $a+b$, $ab(a+b)$, and $ab/(a+b)$ for a number of standard sizes of ribbon.

For any given temperature, the equations may be still further simplified. For example, most heat-treating furnaces are designed for operation at 1850 deg. fahr. Under these conditions, Equations (38) to (47), inclusive, become,

Round Rod

$$D = 0.00713 \sqrt[3]{\frac{I^2 m}{C}} \quad (48a)$$

$$D = \frac{0.007485 m L^2 C}{E^2} \quad (49a)$$

$$D = 4,473,000 \frac{C}{Q^2 m} \quad (50a)$$

Flat Ribbon

$$a b (a + b) = 0.0000004472 \frac{I^2 m}{C} \quad (48b)$$

$$\frac{a b}{(a + b)} = 0.003742 \frac{m L^2 C}{E^2} \quad (49b)$$

$$\frac{a b}{(a + b)} = 2,236,500 \frac{C}{Q^2 m} \quad (50b)$$

made with the aid of Table II, the range of sizes making it impractical and inaccurate to plot them.

TABLE II

Width in inches <i>a</i>	Thickness in inches <i>b</i>	B & S gage number	Cross-sectional area in square inches <i>a b</i>	Semi-perimeter in inches <i>a + b</i>	<i>a b (a + b)</i>	$\frac{a b}{a + b}$
$\frac{1}{16}$	0.0640	14	0.00400	0.127	0.000506	0.0316
	0.0510	16	0.00319	0.114	0.000362	0.0281
	0.0400	18	0.00250	0.103	0.000256	0.0244
	0.0320	20	0.00200	0.0945	0.000189	0.0212
	0.0253	22	0.00158	0.0878	0.000139	0.0180
	0.0201	24	0.00126	0.0826	0.000104	0.0152
	0.0159	26	0.000994	0.0784	0.0000779	0.0127
	0.0126	28	0.000788	0.0751	0.0000591	0.0105
	0.0100	30	0.000675	0.0725	0.0000453	0.00862
	0.0080	32	0.000500	0.0705	0.0000353	0.00709
	0.0063	34	0.000394	0.0688	0.0000271	0.00572
	0.0050	36	0.000313	0.0675	0.0000211	0.00463
	0.0040	38	0.000250	0.0665	0.0000166	0.00376
	0.0030	40	0.000188	0.0655	0.0000123	0.00286
$\frac{1}{8}$	0.0640	14	0.00800	0.189	0.00151	0.0423
	0.0510	16	0.00638	0.176	0.00112	0.0362
	0.0400	18	0.00500	0.165	0.000825	0.0303
	0.0320	20	0.00400	0.157	0.000628	0.0255
	0.0253	22	0.00316	0.150	0.000475	0.0210
	0.0201	24	0.00251	0.145	0.000365	0.0173
	0.0159	26	0.00199	0.141	0.000280	0.0141
	0.0126	28	0.00158	0.138	0.000217	0.0114
	0.0100	30	0.00125	0.135	0.000169	0.00926
	0.0080	32	0.00100	0.133	0.000133	0.00752
	0.0063	34	0.000788	0.131	0.000103	0.00600
	0.0050	36	0.000625	0.130	0.0000813	0.00481
	0.0040	38	0.000500	0.129	0.0000645	0.00388
	0.0030	40	0.000375	0.128	0.0000480	0.00293
$\frac{1}{4}$	0.0640	14	0.0160	0.314	0.00502	0.0510
	0.0510	16	0.0128	0.301	0.00384	0.0424
	0.0400	18	0.0100	0.290	0.00290	0.0345
	0.0320	20	0.00800	0.282	0.00226	0.0284
	0.0253	22	0.00633	0.275	0.00174	0.0230
	0.0201	24	0.00503	0.270	0.00136	0.0186
	0.0159	26	0.00398	0.266	0.00106	0.0149
	0.0126	28	0.00315	0.263	0.000827	0.0120
	0.0100	30	0.00250	0.260	0.000650	0.00962
	0.0080	32	0.00200	0.258	0.000516	0.00775
	0.0063	34	0.00158	0.256	0.000404	0.00615
	0.0050	36	0.00125	0.255	0.000319	0.00490
	0.0040	38	0.00100	0.254	0.000254	0.00394
	0.0030	40	0.000750	0.253	0.000190	0.00296
$\frac{1}{2}$	0.0640	14	0.0320	0.564	0.0180	0.0567
	0.0510	16	0.0255	0.551	0.0141	0.0463
	0.0400	18	0.0200	0.540	0.0108	0.0370
	0.0320	20	0.0160	0.532	0.00851	0.0301
	0.0253	22	0.0127	0.525	0.00665	0.0241
	0.0201	24	0.0101	0.520	0.00523	0.0193
	0.0159	26	0.00795	0.516	0.00410	0.0154
	0.0126	28	0.00630	0.513	0.00323	0.0123
	0.0100	30	0.00500	0.510	0.00255	0.00980
	0.0080	32	0.00400	0.508	0.00203	0.00787
	0.0063	34	0.00315	0.506	0.00159	0.00622
	0.0050	36	0.00250	0.505	0.00126	0.00495
	0.0040	38	0.00200	0.504	0.00101	0.00397
	0.0030	40	0.00150	0.503	0.000755	0.00298
$\frac{3}{4}$	0.0640	14	0.0480	0.814	0.0391	0.0590
	0.0510	16	0.0383	0.801	0.0306	0.0478
	0.0400	18	0.0300	0.790	0.0237	0.0380
	0.0320	20	0.0240	0.782	0.0188	0.0307
	0.0253	22	0.0190	0.775	0.0147	0.0245
	0.0201	24	0.0151	0.770	0.0116	0.0196
	0.0159	26	0.0119	0.766	0.00913	0.0156
	0.0126	28	0.00945	0.763	0.00721	0.0124
	0.0100	30	0.00750	0.760	0.00570	0.00987
	0.0080	32	0.00600	0.758	0.00455	0.00792
	0.0063	34	0.00473	0.756	0.00357	0.00625
	0.0050	36	0.00375	0.755	0.00283	0.00497
	0.0040	38	0.00300	0.754	0.00226	0.00398
	0.0030	40	0.00225	0.753	0.00169	0.00299

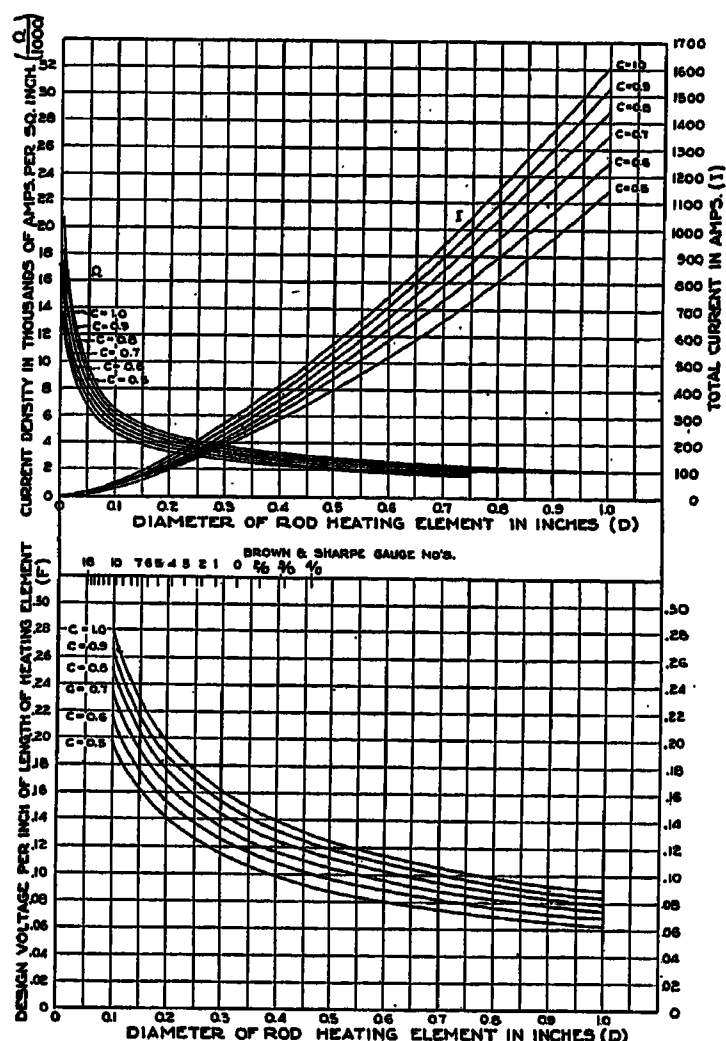


FIG. 3—THEORETICAL DESIGN CURVES FOR NICKEL-CHROMIUM ROD HEATING ELEMENTS IN ELECTRIC FURNACES OPERATING AT 1850 DEG. FAHR.

$$D = \frac{0.007485 m C}{F^2} \quad (51a) \quad \frac{a b}{(a + b)} = 0.003742 \frac{m C}{F^2} \quad (51b)$$

$$D = \frac{1.078 m C}{F'^2} \quad (52a) \quad \frac{a b}{(a + b)} = \frac{0.539 m C}{F'^2} \quad (52b)$$

For any value of C , these relationships provide complete design data. In the case of the round rod, they may be plotted. Fig. 3 shows Equations (48a), (50a), and (51a). The flat ribbon calculations are readily

TABLE II—Continued

Width in inches <i>a</i>	Thickness in inches <i>b</i>	B & S gage number	Cross- sectional area in square inches <i>a b</i>	Semi- perimeter in inches <i>a + b</i>	<i>a b(a + b)</i>	$\frac{a b}{a + b}$
1	0.0640	14	0.0640	1.0640	0.0681	0.0602
	0.0510	16	0.0510	1.0510	0.0536	0.0485
	0.0400	18	0.0400	1.0400	0.0416	0.0385
	0.0320	20	0.0320	1.0320	0.0330	0.0310
	0.0253	22	0.0253	1.0253	0.0259	0.0247
	0.0201	24	0.0201	1.0201	0.0205	0.0197
	0.0159	26	0.0159	1.0159	0.0162	0.0157
	0.0126	28	0.0126	1.0126	0.0128	0.0124
	0.0100	30	0.0100	1.0100	0.0101	0.00990
	0.0080	32	0.0080	1.0080	0.00806	0.00794
	0.0063	34	0.0063	1.0063	0.00634	0.00626
	0.0050	36	0.0050	1.0050	0.00503	0.00498
	0.0040	38	0.0040	1.0040	0.00402	0.00398
	0.0030	40	0.0030	1.0030	0.00301	0.00299
1 $\frac{1}{4}$	0.2500	..	0.313	1.5000	0.469	0.208
	0.1875	..	0.234	1.4375	0.337	0.163
	0.1250	..	0.156	1.3750	0.215	0.114
1 $\frac{1}{2}$	0.1000	..	0.150	1.600	0.240	0.0938
	0.0800	..	0.120	1.580	0.190	0.0759
	0.0700	..	0.105	1.570	0.165	0.0669
	0.0600	..	0.0900	1.560	0.140	0.0577
	0.0500	..	0.0750	1.550	0.116	0.0484
	0.0400	..	0.0600	1.540	0.0924	0.0390
	0.0300	..	0.0450	1.530	0.0689	0.0294
	0.0200	..	0.0300	1.520	0.0456	0.0197
2	0.2500	..	0.500	2.2500	1.125	0.222
	0.1875	..	0.375	2.1875	0.820	0.171
	0.1250	..	0.250	2.1250	0.531	0.118

The equations derived are rigorous in every respect, requiring judgment only in the selection of *C*, which has already been discussed. They are the maximum allowable ratings in each case and cannot be exceeded. Good practise indicates that it is best to allow considerable latitude for safety.

EMPIRICAL RELATIONSHIPS

The equations just derived, and the curves of Figs. 2 and 3, define limiting conditions, which the laws of Nature impose upon industrial heating design. It is to be feared that, in the past, a lack of understanding of these fundamentals has led to a rather haphazard procedure. Guided only by experience and data gathered in the field, the designer has made little or no effort to correlate these with the physical laws.

Strangely enough, however, one empirical relationship which still forms the basis of much design work, approaches remarkably close to the limitations set up by the theory. Yet, when it was first used, no work had been done on the screening effect of nearby objects; it was used because, in almost every case, it gave elements with long life. It is interesting to see why.

The straight line,

$$G = \frac{2100 - T_0}{30} \quad (53)$$

is shown in Fig. 4 (Curve B), in its relation to curve A,—50 per cent radiating efficiency replotted from Fig. 2. It is evident that the line gives an extremely conserva-

tive rating, especially at moderate temperatures, even under such conditions as double banking or close spacing of units. It is interesting to look at curve C in Fig. 4, which is plotted from that given by Woodson⁹ for the design of heating elements outside the vessels of metal melting pots. Although the curve does not conform to the Stefan-Boltzman law, at any radiating efficiency, it is an effort to express the results of experience in this very arduous type of service. The use of such a rating ought to be confined to work where coiled wire is employed in confined spaces. Certainly Equation (53) provides ample allowances for all ordinary purposes, where the element is free to radiate.

It is interesting to see how the expressions derived for proportioning resistors work out, when substituted in Equation (53). This may be written

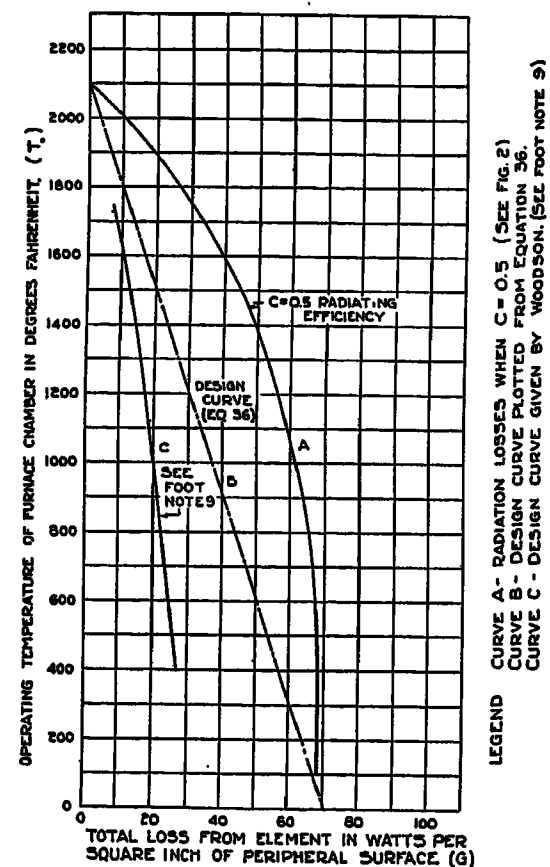


FIG. 4—COMPARISON OF THEORETICAL WITH OTHER RADIATION CURVES FOR NICKEL-CHROMIUM HEATING ELEMENT TEMPERATURE OF 2100 DEG. FAHR

$$T_0 = 2100 - 30 G \quad (54)$$

Substituting for *G* its value from (17) and (18),

Round Rod

$$T_0 = 2100 - \frac{120 I^2 \rho m}{\pi^2 D^3} \quad (55a)$$

$$T_0 = 2100$$

$$- 0.0004974 \frac{I^2 m}{D^3}$$

(56a)

Flat Ribbon

$$T_0 = 2100 - \frac{15 I^2 \rho m}{a b (a + b)} \quad (55b)$$

$$T_0 = 2100$$

$$- 0.0006135 \frac{I^2 m}{a b (a + b)}$$

(56b)

Likewise, from Equations (19) and (20),

<u>Round Rod</u>	<u>Flat Ribbon</u>
$T_0 = 2100 - 7.5 \frac{E^2 D}{m \rho L^2}$	$T_0 = 2100 - 15 \frac{E^2 a b}{m \rho L^2 (a+b)}$
(57a)	(57b)
$T_0 = 2100$	$T_0 = 2100$
$- 183,330 \frac{E^2 D}{m L^2}$	$- 36,660 \frac{E^2 a b}{m L^2 (a+b)}$
(58a)	(58b)

Using Equations (24) and (25) in (53), for

<u>Round Rod</u>	<u>Flat Ribbon</u>
$T_0 = 2100 - 7.5 Q^2 \rho D m$	$T_0 = 2100 - 15 \frac{Q^2 m \rho a b}{(a+b)}$
(59a)	(59b)
$T_0 = 2100$	$T_0 = 2100$
$- 0.00030675 Q^2 D m$	$- 0.0006135 \frac{Q^2 m a b}{(a+b)}$
(60a)	(60b)

And from Equations (28), (29), (30), and (31), respectively, for

<u>Round Rod</u>	<u>Flat Ribbon</u>
$T_0 = 2100 - 7.5 \frac{F^2 D}{\rho m}$	$T_0 = 2100 - 15 \frac{F^2 a b}{m \rho (a+b)}$
(61a)	(61b)
$T_0 = 2100$	$T_0 = 2100$
$- 183,330 \frac{F^2 D}{m}$	$- 366,660 \frac{F^2 a b}{m (a+b)}$
(62a)	(62b)
$T_0 = 2100 - \frac{F'^2 D}{19.2 \rho m}$	$T_0 = 2100 - \frac{F'^2 a b}{9.6 m \rho (a+b)}$
(63a)	(63b)
$T_0 = 2100$	$T_0 = 2100$
$- 1272.9 \frac{F'^2 D}{m}$	$- 2546.4 \frac{F'^2 a b}{m (a+b)}$
(64a)	(64b)

These relationships give ready means of proportioning heating elements safely for any furnace operating temperature, directly from their physical dimensions and the electrical characteristics of the furnace circuit. As before, the simplification may be carried one step further. At a maximum temperature of 1850 deg. fahr., with T_0 equal to 1850 deg., a very simple set of results appears:

<u>Round Rod</u>	<u>Flat Ribbon</u>
$D = 0.01257 \sqrt[3]{I^2 m}$	$a b (a+b)$
(65a)	(65b)

$$D = 0.001363 \frac{m L^2}{E^2} \quad (66a) \quad \frac{a b}{(a+b)} = 0.0006813 \frac{m L^2}{E^2} \quad (66b)$$

$$D = \frac{814,900}{Q^2 m} \quad (67a) \quad \frac{a b}{(a+b)} = \frac{407,400}{Q^2 m} \quad (67b)$$

$$D = 0.001363 \frac{m}{F^2} \quad (68a) \quad \frac{a b}{(a+b)} = 0.0006813 \frac{m}{F^2} \quad (68b)$$

$$D = 0.1964 \frac{m}{F'^2} \quad (69a) \quad \frac{a b}{(a+b)} = 0.09818 \frac{m}{F'^2} \quad (69b)$$

To aid in using these equations, some of them, (Nos. (65a), (67a), and (68a)) are plotted in Fig. 5.

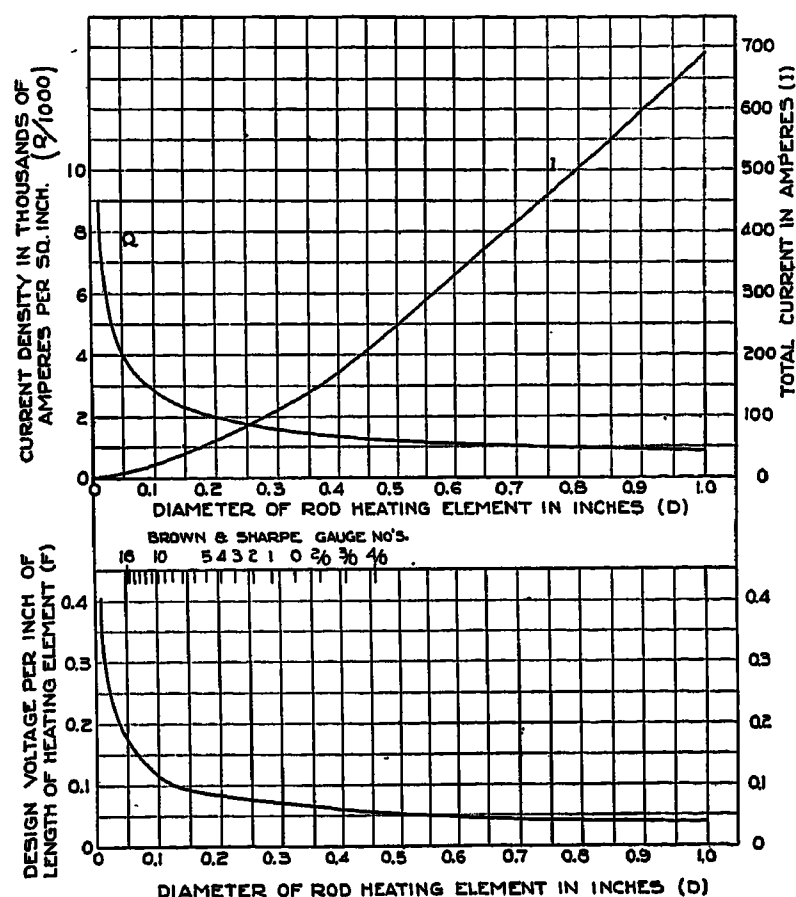


FIG. 5—DESIGN CURVES FOR NICKEL-CHROMIUM ROD HEATING ELEMENTS IN ELECTRIC FURNACES OPERATING AT 1850 DEG. FAHR. (BASED ON CURVE B, FIG. 4)

If the designer is interested in more accurate design, he may use the theoretical curves, Fig. 3, instead of the empirical ones just discussed. He must then apply his own factors of safety, a matter which requires considerable experience.

It should be observed that all of the equations in which the expression ρ appears are perfectly general, applying to both metallic and non-metallic resistors, provided the proper value of m is taken for the temperature of operation.

NUMERICAL EXAMPLE

It may be of interest to carry through the design of a heating element by the two methods, to see what difference is obtained.

For example, assume that it is desired to design the heating elements for a 20-kw. furnace, to operate on 220 volts, single-phase with maximum operating temperature of 1850 deg. fahr. and $C = 0.5$.

The current required will be

$$\frac{20,000}{220} = 90.9 \text{ amperes.}$$

From the curves, Fig. 3, it is evident that 90.9 amperes is permissible in a diameter of 0.185, to which No. 4 B & S gage is the nearest standard size. Directly beneath, the voltage per in. of length is 0.1459, and the required length is, therefore,

$$\frac{220}{0.1459} = 1508 \text{ in., or 125.6 ft.}$$

If the ribbon is to be used, the value of $a b (a + b)$ from Equation (48b) is

$$a b (a + b) = \frac{0.0000004472 \times (90.9)^2 \times 1.05}{0.5} = 0.00776$$

In Table II, various values of $a b (a + b)$ are given. The nearest size to this value is 1 in. $\times$ 0.008 in.

Corresponding to 1 in. $\times$ 0.008 in., the value of $a b / (a + b)$ is 0.00794 so that, from Equation (51b), we have

$$F^2 = \frac{0.003742 \times 1.05 \times 0.5}{0.00794}$$

$F = 0.4972$ volts per inch.
and the length

$$L = \frac{220}{0.4972} = 442.3 \text{ in. or 36.86 ft.}$$

Two other sizes come near the desired value of $a b (a + b)$. These are $\frac{3}{4}$ in. $\times$ 0.0159 in., of which 619.9 in., or 51.65 ft. would be needed; and $\frac{1}{2}$ in. $\times$ 0.032 in., which would have to be 861.1 in., or 71.77 ft. long.

Using the curve for I , Fig. 5, it is seen that 90.9 amperes is the allowable current flow in a diameter of 0.258, which is No. 2, B & S gage. The voltage per in. of length may now be found, on the F curve. The value is 0.0744 volts per in. Hence, the length required is $220/0.0744 = 2956$ in. or 246.35 ft.

In the case of ribbon, the value of $a b (a + b)$ can be obtained from Equation (65b).

$$a b (a + b) = 0.000002455 \times (90.9)^2 \times 1.05 = 0.0213$$

In Table II, the nearest size to this value would be $\frac{3}{4}$ in. $\times$ 0.04 in. ribbon. For this, the value of $a b / (a + b) = 0.0380$.

Using Equation (68b), we have

$$0.0380 = \frac{0.0006813 \times 1.05}{F^2}$$

$$F = 0.1372 \text{ volts per in.}$$

The total length then is $\frac{220}{0.1372} = 1603$ in., or 133.6 ft.

Another size approaches fairly closely in the table. This is 1 in. $\times$ 0.0253, for which $a b / (a + b) = 0.0247$ and $F = 0.1702$; whence the required length is 1292 in. or 107.95 ft.

The designer may choose whichever of the elements best suits the space available in the furnace and the manner of mounting. The theoretical values are as follows:

<i>Round Rod</i>	<i>Flat Ribbon</i>
125.6 ft. of No. 4 wire	36.86 ft. of 1-in. $\times$ 0.008-in. ribbon
	51.65 ft. of $\frac{3}{4}$ -in. $\times$ 0.0159-in. ribbon
	71.77 ft. of $\frac{1}{2}$ -in. $\times$ 0.032-in. ribbon

Conservative practise dictates that the empirical values provide some factor of safety; and, although they involve the use of more metal, they mean lower ratings, decreased element temperatures, greater mechanical strength, and longer life. They are:

<i>Round Rod</i>	<i>Flat Ribbon</i>
246.35 ft. of No. 2 wire	107.95 ft. of 1-in. $\times$ 0.0253-in. ribbon
	133.6 ft. of $\frac{3}{4}$ -in. $\times$ 0.04-in. ribbon

CONCLUSION

The derivation of fundamental equations for use in the design of electric heating elements has shown what are the physical limitations of the problem. As a sequel thereto, it has been found that one of the earliest rules-of-thumb gives good factors of safety at all electric furnace temperatures. The use of this relationship is to be commended, in the interest of conservatism, bearing in mind that the best design still relies upon the scanty information available about the material of which the heating elements are constructed.

Discussion

J. Ormondroyd: (communicated after adjournment) Footnote No. 2, p. 1199 in common with all publications on this subject that I have seen, assumes that it is so easy to show the compatibility between the Stefan-Boltzman Law and Planck's Law, that the actual work is never given. It is easy to derive the older law from the newer one but most readers feel uncomfortable when they let the mere claim of ease pass for a detailed proof. My comment merely consists of this detailed proof as follows:

Planck's equation giving energy intensity for every wavelength.

$$u_2 = c_1 \lambda^{-5} \left[e^{\frac{c_2}{\lambda T}} - 1 \right]^{-1} \text{ watts per sq. cm.} \quad (1)$$

where

λ wave length in μ

T abs. temp. centigrade

This can be expanded into a series by means of the Binomial Theorem.

$$u_{\lambda} = c_1 \sum_{n=1}^{\infty} \lambda^{-n} e^{-\frac{n c_2}{\lambda T}} \text{ watts per sq. cm.} \quad (2)$$

The total radiation over the whole spectrum is

$$U = c_1 \sum_{n=1}^{\infty} \int_0^{\infty} \lambda^{-n} e^{-\frac{n c_2}{\lambda T}} d\lambda \text{ watts per sq. cm.} \quad (3)$$

Integrating by parts

$$\int_0^{\infty} \lambda^{-n} e^{-\frac{n c_2}{\lambda T}} d\lambda = \left| e^{-\frac{n c_2}{\lambda T}} \left[\lambda^{-n} \frac{T}{n c_2} + \lambda^{-n+1} \frac{3 T^2}{n^2 c_2^2} + \lambda^{-n+2} \frac{6 T^3}{n^3 c_2^3} + \lambda^{-n+3} \frac{6 T^4}{n^4 c_2^4} \right] \right|_0^{\infty} = \frac{6 T^4}{n^4 c_2^4} \quad (4)$$

When the limit $\lambda = 0$ is substituted in (4), the indeterminate form $e^{-\frac{k}{\lambda}} \lambda^{-a} = 0 \cdot \infty$ appears. This can be shown to be equal to zero.

From (3) and (4) the total radiation is

$$U = c_1 \sum_{n=1}^{\infty} \frac{6 T^4}{n^4 c_2^4} = \frac{6 c_1}{c_2^4} \sum_{n=1}^{\infty} \frac{1}{n^4} T^4 \quad (5)$$

$$\sum_{n=1}^{\infty} \frac{1}{n^4} = \frac{\pi^4}{90} \quad (6)$$

$$c_1 = 3.7 \times 10^4 \text{ for } u \text{ in watts per sq. cm.} \quad (7)$$

$$c_2 = 14325 \text{ for } \lambda \text{ in } \mu \quad (8)$$

Therefore

$$\frac{6 c_1 \pi^4}{c_2^4 90} T^4 = 5.72 \times 10^{-12} T^4 \text{ watts per sq. cm.} \quad (9)$$

The value of the Stefan-Boltzman Constant given in the Smithsonian Tables is 5.71×10^{-12} .

Edwin Fleischmann: Mr. Ormondroyd's derivation of the Stefan-Boltzman Law from Planck's Equation serves as a valuable supplement, completing the fundamental background of the derivations given in the paper. It explains and substantiates the reference and statement of footnote 2.

Safe Loading of Oil-Immersed Transformers

E. T. NORRIS¹

Member, A. I. E. E.

Synopsis.—An attempt is made to describe simply and clearly the basis of the temperature rating of oil-immersed transformers and the relations between the temperatures measured in service, the maximum safe output rating, and the national standard ratings.

A description is given of an instrument for indicating the safe output rating of a transformer in service under any conditions of short time or continuous loading.

LIST OF SYMBOLS

- A = Temperature of cooling medium—usually air or water.
 D = Maximum variation in temperature of the circulating oil.
 G = Maximum winding temperature difference.
 G_a = Average winding temperature difference.
 H = Hottest spot temperature.
 h = $H - A$.
 K = Constant.
 N = Ratio copper to iron loss at full load.
 P = Load on transformer as a fraction of full load.
 R = Average temperature of the winding by resistance.
 r = $R - A$.
 T = Hottest oil temperature.
 t = $T - A$.

As the load current in an oil-immersed transformer is increased, its temperature rises due to the increase in losses. One limit to the load which may be taken from a transformer is, therefore, set by the maximum temperature permissible.

BASIS OF OUTPUT RATING

The material most susceptible to damage by heat in a transformer is the insulation. The fundamental basis of the rating of the transformer is, therefore, the maximum temperature the insulation will safely withstand. The temperature of the hottest part of the insulation of the transformer (or the hottest spot temperature H) must never be allowed to exceed this safe limit.

The limit applies, of course, to the insulation both in the core and in the windings. Since, however, the core losses are practically constant for all loads, whereas the copper or winding losses increase rapidly with the load, it is the winding insulation which is most affected by the loading, and its hottest spot temperature which determines the safe maximum load.

If it were possible to measure the hottest spot temperature while the transformer was in operation, it would be a simple matter to determine the maximum safe rating and to ensure that it was not exceeded. Unfortunately, except in a few special instances, there are no known practical means of measuring this temperature directly.

1. Chief designer, Ferranti, Ltd., London, England.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

As a rule, it is not possible to employ thermocouples or other forms of embedded temperature detector in such a way as not to weaken the transformer insulation and yet to record accurately the true hottest spot temperature, and to be safe in operation. This position has recently been confirmed by a meeting of the International Electrotechnical Commission.

The most useful practical temperature measurements are:

a. The temperature of the hottest oil by thermometer = T .

This temperature is easily measured and a continuous record can be obtained whilst the transformer is in service. It does not, however, follow closely short time load variations.

b. The average temperature R of the windings calculated from the resistance.

This measurement is mainly suitable under testing conditions. It is necessary to disconnect the transformer in order to measure the resistance, so that readings cannot be obtained during operation. The temperature measured is the average temperature of the whole winding.

To determine the maximum safe rating of a transformer from these two temperatures, it is necessary to know the relations between these temperatures and the hottest spot temperature.

STANDARD OUTPUT RATINGS

It is important to distinguish between the true thermal rating of a transformer and its rating in accordance with a standard specification.

The true thermal rating is determined by the maximum safe hottest spot temperature. It is not a constant for a given transformer, but may have any value depending on the conditions of loading and cooling.

The primary purpose of a national standard specification is to provide a basis for the comparison of transformers of different makes and types. The standard rating must be so defined that it can be determined easily and accurately in practice, and is, therefore, expressed in terms of the observable temperatures R and T . It is based on certain definite loading and cooling conditions so as to be a constant for a given transformer.

The manner in which the observable temperatures R and T are derived from the hottest spot temperature for standardization purposes, is explained in Pamphlet No. 1 of the A. I. E. E. Standards.

Typical values of these observable temperatures after continuous rated load for the standards of three countries are given in Table I. The standards specify both these limiting temperatures and state that neither may be exceeded.

TABLE I

Country	Self-cooling		Forced-cooling	
	<i>R</i>	<i>T</i>	<i>R</i>	<i>T</i>
U. S. A.	95	90	80	..
Britain.	95	90	90	75
Germany.	105	95	..	..

The kv-a. output of a transformer depends on its temperature rise above the temperature of the cooling medium. The output can, therefore, be increased:

a. By raising its working temperature until the maximum safe hot spot limit is reached.

b. By reducing the temperature of its cooling medium. Hence, to standardize the output rating of a transformer, the temperature rise must be specified. A complete standard specification includes the two observable temperatures *R* and *T* together with the temperature of the cooling medium.

Typical values of the cooling medium temperature *A* together with the resulting temperature rises are given in Table II.

TABLE II

Country	Self-cooling			Forced-cooling		
	<i>A</i>	<i>r</i>	<i>t</i>	<i>A</i>	<i>r</i>	<i>t</i>
U. S. A.	40	55	50	25	55	..
Britain.	40	55	50	25	65	50
Germany.	35	70	60	..	..	..

The cooling medium temperature *A* is the temperature of the ambient air in self-cooled transformers, and of the inlet water in water-cooled transformers.

A transformer complying with a standard specification will have temperature rises measured in oil and by resistance not exceeding these limits, but not necessarily reaching the limits.

The relations between *T*, *R* and *H* for any given transformer depend upon the thermal design, and may vary widely for transformers of the same standard rating but of different types or makes. The design conditions are frequently such that, in order that *R* may be within the specified limits, the value of *T* must be lower than the maximum the specification allows.

A British Standard rated transformer, for example, with an oil temperature rise less than 50 deg. cent. at full load, is not necessarily running below its true standard rating since the temperature rise by resistance may be up to the full standard limit.

The loading and cooling conditions chosen by all the standardization authorities are extreme. The British and American standards, for example, assume full load continuously, and an ambient air temperature of

40 deg. cent. continuously for self-cooled transformers—operating conditions which are rarely encountered in practise.

An apparent advantage of this basis is that the standard rating is very conservative and may safely be worked to in almost any climate and under any loading conditions.

It has become general practise for operating engineers to consider the standard rating as being the maximum safe rating under normal working conditions. Transformers much larger than is necessary are therefore installed.

A relatively minor disadvantage of this position is waste in transformer plant installed and in exciting kv-a. and losses.

A more serious result is that operating experience cannot distinguish between transformers of good and bad thermal design. Undesirable opportunity is thereby given to the unskilled or unscrupulous manufacturer, and lessons of experience which are essential to progress in design and construction are lost to the industry.

It is suggested that the use of hottest spot temperature indicators be encouraged in standard specifications; that distinction be made between the true thermal rating and the standard rating, as described earlier in the paper; and that alternative standard ratings be recognized covering more practical operating conditions.

TEMPERATURE DISTRIBUTION IN A TRANSFORMER

The main parts of any type of oil-immersed transformer are the iron core, the windings, the tank, and the oil. During operation, heat is generated in the iron core and in the copper of the windings.

Considering only steady-load conditions, the heat must be transferred to the cooling medium air or water. The oil serves as the transference agent. Heat flows by conduction to the surface of the material into the oil and thence by thermal transference to the cooling medium.

The oil circulates in a closed path between the transformer and the cooling medium, rising in temperature as it collects heat from the transformer and falling in temperature as it delivers it to the cooling medium. This variation in oil temperature *D* has a large effect on the thermal design of the transformer. For a given specific heat of oil there is a definite relation between the temperature difference *D*, the quantity of oil in circulation, and the heat losses being dissipated.

The oil circulation path is shown diagrammatically for three types of cooling in Fig. 1, but is not, of course, actually so directly and clearly defined as in the figures. In self-cooled transformers the oil circulation depends on the tank dimensions and winding arrangement. In water-cooled transformers it can be controlled to some extent by varying the cooling conditions, and in forced oil-cooled transformers the circulation is completely under control, and *D*, for instance, can be given any desired value.

WINDING THERMAL CONDITIONS

A transformer winding with oil flowing through it is shown diagrammatically in Fig. 2. The temperature T of the oil leaving the windings is here assumed to be the same as the temperature of the hottest oil. This is so in most practical cases. Where the difference is appreciable, however, an average value can be assumed which will give sufficiently accurate results for the present purpose. The same conditions apply to the increase of oil temperature D .

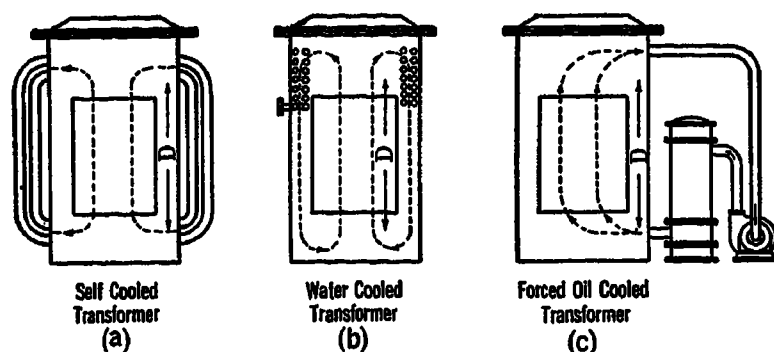


FIG. 1

The temperature of the oil at the bottom of the windings will be $(T - D)$.

The relation between the winding temperature at any point and the adjacent oil temperature depends largely upon which of the following conditions holds:

1. The direction of oil flow is at right angles to the conductors in the winding.
2. The direction of oil flow is parallel with the conductors in the winding.

Condition (1) applies to most core type and some shell type transformers.

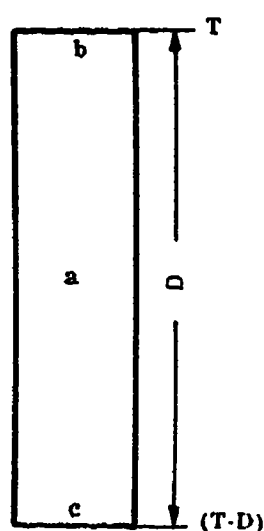


FIG. 2

Condition (2) applies to many shell type transformers.

Under condition (1), considering only a steady continuous load and assuming the windings are fairly symmetrical, the hottest spot temperature of the insulation at any point such as a or b in Fig. 1 will be a constant value G above the adjacent oil temperature. The hottest spot temperature of the copper, and, therefore, of the adjacent insulation at c , for example, will be $(T - D + G)$.

The hottest spot temperature H of the copper for

the whole winding will be at some point b and such that

$$H = T + G \quad (1)$$

This temperature H must not under any conditions of loading exceed the safe limit, *e. g.*, 105 deg. cent. for I. E. C. rating.

Under condition (2) the thermal gradient in the winding in the direction of the conductors will be short-circuited by the copper, since the thermal conductivity of copper is approximately 2000 times that of the winding insulation. The temperature of the winding will be constant in the direction parallel to the flow of the oil. The winding temperature difference will not then be constant as in the previous case. At the top of the windings it will be $(H - T)$ and at the bottom $(H - T + D)$. If G is the value at the top of the windings, then:

$$H = T + G$$

as in Equation (1).

The temperature R measured by increase of resistance of the windings will be the average temperature of the copper in the windings taking the average in directions both normal and parallel to the flow of oil.

Under condition (1) its equivalent is the temperature of the copper at some point near the center of the winding such that:

$$R = T - K D + G_a \quad (2)$$

For condition (2) the temperature of the copper is constant at all points in a vertical direction. Assuming G_a is the average value of the winding temperature difference at the top of the windings, then:

$$R = T + G_a \quad (2a)$$

Comparison of this relation with Equation (2) shows that if the flow of oil is parallel to the conductors, K becomes zero.

It should be noted, however, that the direction of oil flow cannot in practice be parallel to the conductors for the whole of the winding. The temperature relations for condition (2) will, therefore, apply to part only of the winding, and for all types of transformers K will be greater than zero.

Equation (2) gives the relation between R and T in any oil-immersed transformer. G_a is the average value of the winding temperature difference taken in a radial direction through the coil. It is usually within 5 deg. cent. of the maximum value G .

The constant K varies between 0.1 and 0.6 depending on the thermal design.

As previously explained, most national standards fix upper limits for both R and T . The designer of the transformer has, therefore, so to adjust D and G_a that neither of these limits is exceeded.

The value of D itself varies widely from 1 deg. cent. to 15 deg. cent. for forced-oil-cooled transformers, and from 5 deg. cent. to 30 deg. cent. for self-cooled and water-cooled transformers. For an A. I. E. E. or B. S. rated self-cooled core type transformer in which both oil and

winding temperatures are at their limits, Equation (2) becomes, assuming $D = 20$ and $K = 0.4$

$$95 = 90 - 8 + G a$$

or $G a = 13$ deg. cent.

In many cases a cheaper and better design could be made if $G a$ were larger than 13. For a self-cooled transformer D cannot be varied much, so that $G a$ can only be increased by reducing the hottest oil temperature T . The revised figures might be:

$$95 = 80 - 8 + G a$$

giving $G a = 23$ deg. cent. instead of 13 deg. cent. Such a transformer at full load and with 40 deg. cent. air would have a temperature rise by resistance of 55 deg. cent.—the standard limit—but the hottest oil rise would only be 40 deg. cent. or 10 deg. cent. below the standard limit.

This example shows clearly why a B. S. or A. I. E. E. rated self-cooled transformer with hot oil rise 10 deg. cent. below the specified value is not necessarily liberally rated. In this case, the load could not be increased until the oil rise reached 50 deg. cent. without seriously exceeding the standard rating.

RELATION BETWEEN THE AVERAGE WINDING TEMPERATURE AND THE HOTTEST SPOT TEMPERATURE

Equation (2) gives the relation between the average winding and hottest oil temperature. For standardization purposes these observable temperatures are derived from the safe hottest spot temperature by arbitrary relations.

Combining Equation (1) and (2) gives the relation between the hottest spot and the average winding temperatures.

$$H = R + K D + G - G a \quad (3)$$

Thus the difference between the hottest spot temperature H and the average winding temperature R is $(K D + G - G a)$. This value is assumed by the A. I. E. E., for example, as 10 deg. cent. for O. I. S. C. transformers.

In forced-oil-cooled and water-cooled transformers where D can be more or less controlled, Equation (3) shows the advantage in having a small value for standard rated transformers. As an example, consider a British Standard rated oil-immersed, forced-cooled transformer with inlet water at 25 deg. cent. After steady continuous load $R = 90$ deg. cent. from Table I.

From Equation (3) assuming $(G - G a) = 2$ deg. cent., the hottest spot temperature is:

$$H = 92 + .5 D$$

If the design of the oil cooler is such that $D = 16$ deg. cent., then the hottest spot temperature = 100 deg. cent.

If, however, for the same winding temperature rise the value of D is 2 deg. cent., then the hottest spot temperature is only 93 deg. cent., a reduction of 7 deg. cent.

These two transformers both comply nominally with the British Standard Specification without any margin, yet the latter transformer is actually working at a considerably lower hottest spot temperature, and has therefore a higher safe output rating.

EFFECT OF COOLING MEDIUM TEMPERATURE ON THE OUTPUT RATING

So far, the final temperatures have been considered mainly as it is these which determine the maximum permissible loading.

The output of any given transformer depends on its temperature rise above the cooling medium, and this rise determines the rating of the transformer provided that the safe hottest spot temperature is not exceeded.

Equations (1)-(3) are equally true of the temperature rises above the temperature of the cooling medium instead of the final temperature H , R , and T are inserted. Calling these temperature rises h , r , and t respectively:

$$h = t + G \quad (4)$$

$$r = t - K D + G a \quad (5)$$

$$h = r + K D + G - G a \quad (6)$$

The true effect of load variations on the temperatures in Equations (1)-(6) is complicated no matter whether actual temperatures or temperature rises are considered. None of the temperatures is a simple function either of the load or of the losses. The temperature rise of the hottest oil, for example, usually varies as something less than the first power of the total losses. The winding temperature difference is often not directly proportional to the copper losses. Factors contributing to this complication are variations in the copper losses and in the viscosity and other characteristics of oil with temperature.

As a rough approximation, especially for self-cooled transformers, it will be assumed that the oil temperature variation D and the hottest oil rise t are directly proportional to the total losses, and that the winding gradient is directly proportional to the copper losses. These assumptions will give results on the safe side when considering permissible overloads.

On this basis any of Equations (1)-(6) may be rewritten for any desired load.

Applying these relations to Equation (2) shows that R will increase faster than T as the load increases. The hottest spot temperature similarly increases faster than T . Herein lies the danger of estimating overloads and the effect of load variations from the oil rise t only.

For example, assume an A. I. E. E. rated transformer giving the following result in Equation (5) at full load.

$$55 = 45 - 8 + 18$$

If the copper loss is equal to the iron loss at full load, then at 30 per cent overload continuously the copper losses, neglecting the effect of temperature on the resistance of the windings, will be 1.69 times, and the

total losses 1.34 times the original values, and Equation (5) becomes:

$$80.1 = 1.34 (45 - 8) + 1.69 \times 18 = 60.5 - 10.8 + 30.4$$

Thus on overload the oil rise has increased 15.5 deg. or 34 per cent whilst the winding rise has increased 25.1 deg. or 46 per cent.

The greater relative increase in winding temperature rise would be even more marked for short time overloads.

It is now possible to estimate the effect on the permissible loading of variations in the temperature of the cooling medium. The method can be most clearly shown by an example.

Consider an A. I. E. E. rated self-cooled transformer with the following thermal characteristics after continuous full load with an ambient air temperature of 40 deg. cent. These values are typical of a medium sized self-cooled core type transformer.

$$R = 95 \quad D = 20 \quad G_a = 18 \quad G = 20$$

$$T = 85 \quad H = 105 \quad K = 0.4$$

Ratio of copper to iron losses = $N = 2$

$$\text{Equation (2) becomes } 95 = 85 - 8 + 18 \quad (7)$$

$$\text{Equation (1) becomes } 105 = 85 + 20$$

Suppose the ambient temperature is only 25 deg. cent. At full load $R = 80$ deg. cent., $T = 70$ deg. cent., and $H = 90$ deg. cent. The load may safely be increased until H is raised to 105 deg. cent., *i. e.*, h may increase to 80 deg. cent.

Let P = the new permissible load as a fraction of normal full load

The new total losses will be $\frac{P^2 N + 1}{N + 1}$ times normal.

The new copper losses will be P^2 times normal.

Equation (4) becomes:

$$80 = \frac{2 P^2 + 1}{3} \times 45 + 20 P^2$$

whence $P = 1.14$

Hence the effect of reducing the ambient temperature from 40 deg. cent. to 25 deg. cent. is to increase the output rating of the transformer 14 per cent.

At this overload with an air temperature of 25 deg. cent. the hottest spot temperature will be 105 deg. cent. and Equation (2) will read

$$92.8 = 79 - 9.6 + 23.4 \quad (8)$$

It is instructive to compare (7) and (8). Both the hottest oil and winding temperatures are lower in the second case, but the transformer is equally loaded thermally in the two cases.

The above method of determining the effect of ambient temperature on rating may be expressed conveniently in a formula giving the permissible loading at any air temperature.

$$P = \sqrt{\frac{(H - A)(N + 1) - t_n}{G_n(N + 1) + N t_n}} \quad (9)$$

Where P = permissible load in terms of normal.

A = temperature of cooling medium.

H = maximum safe hottest spot temperature.

N = ratio copper loss to iron loss at normal load.

G_n and t_n = values at normal load.

Using Equation (9) a curve can be plotted for any given transformer showing the permissible loading without exceeding a given safe hottest spot temperature for varying air temperatures. In the present example, Equation (9) becomes:

$$P = \sqrt{\frac{90 - A}{50}}$$

Fig. 3 shows the curve of overload and air temperature.

With such a curve it is easy to check whether the load on a transformer in service is near its maximum safe rating.

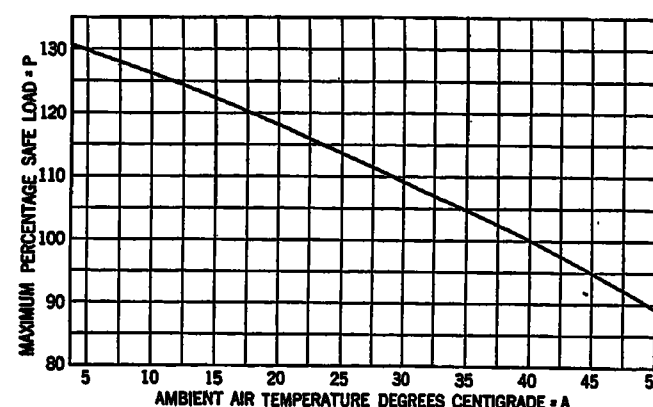


FIG. 3

Similar curves can, of course, be drawn for water cooled and forced-oil-cooled transformers.

An alternative method of obtaining the loading conditions on a transformer in service in which only the temperatures of the cooling medium and the hot oil are required, can be derived from Equations (9) and (1).

Equation (1) at any load P times normal becomes:

$$H = T + P^2 G_n \text{ whence } P = \sqrt{\frac{H - T}{G_n}} \quad (10)$$

where G_n = value at normal load.

Using this value of P in (9) gives:

$$T = H - G_n \frac{(H - A)(N + 1) - t_n}{G_n(N + 1) + N t_n} \quad (11)$$

where T = maximum hot oil temperature permissible at the cooling medium temperature A .
 t_n and G_n = values at normal load.

In the example $T = 69 + 0.4 A$

If the air temperature is 20 deg. cent., the transformer is fully loaded (*i. e.*, its hottest spot temperature is 105 deg. cent.) when the hottest oil temperature is 77 deg. cent. The continuous load to give this condition may be obtained from (10)

$$P = \sqrt{\frac{105 - 77}{20}} = 118\%$$

Hence, by means of Equation (11) readings of the oil and air temperatures for any transformer on constant load show the loading conditions at that time, and indicate the proportion of the maximum permissible load the transformer is carrying.

The formulas developed in this paper are intended for purposes of illustration and exposition rather than for actual application to practical problems. The formulas may, however, be modified to suit particular conditions. For example, the exponent of P in Equation (10) may be adjusted to suit the exact relation between the winding gradient and the load. Incidentally, practical correction for the effect of temperature on the copper losses may be made by adjusting this exponent.

The predetermination of the true thermal rating of transformers requires numerous formulas to cover the wide range of loading and cooling conditions that may occur in practice. None of these formulas would be sufficiently general to be suited to the present purpose. The complete subject has been treated recently by the present author.²

RELATION BETWEEN OIL TEMPERATURE AND OUTPUT RATING

The hottest oil temperature is easily measured on a transformer in service, and it is well, therefore, to examine what information, as to the loading conditions, can be obtained from it.

From Equation (10) $P = \sqrt{\frac{H - T}{G_n}}$ where H and T

are values at load P and G_n is the winding temperature difference at normal load.

In the example $G_n = 20$

$$\text{Hence } P = \sqrt{\frac{105 - T}{20}}$$

This relation is plotted in a curve in Fig. 4. The practical use of the curve has been pointed out by G. L. Porter. It gives the maximum oil temperatures for different loads. If, for instance, in the example the load is 120 per cent, the oil temperature must not be allowed to exceed 76.2 deg. cent. Whether the transformer is able to carry this load continuously depends on the air temperature. Equation (9) or Fig. 3 shows that for this to be possible the ambient temperature must not exceed 18 deg. cent.

The curve may be applied to temporary overloads as well as to continuous loads. An overload of 30 per cent, for instance, in the example may be applied until such a time as the oil temperature reaches 71.2 deg. cent., and this is true no matter what the previous loading conditions, if within the safe rating; *e. g.*, whether the transformer has previously been on full normal load or even on no-load.

If the air temperature is greater than 5.5 deg. cent.

(Equation (9) or Fig. 3), it is only a matter of time before the oil temperature reaches 71 deg. cent. When this happens the load must be reduced. This use of Equation (10) gives results slightly on the safe side for short time heavy overloads of only a few minutes' duration, since it makes no allowance for the thermal time constant of the windings.

Again, suppose at a given instant the oil temperature of this transformer is 75 deg. cent., but the previous loading history is unknown. The curve states that any load up to 122 per cent may safely be taken from the transformer (actually some margin should be allowed here and a somewhat lower limit than 122 per cent assumed). How long this load could be taken depends on the air temperature, but always so long as the oil temperature does not exceed 75 deg. cent.

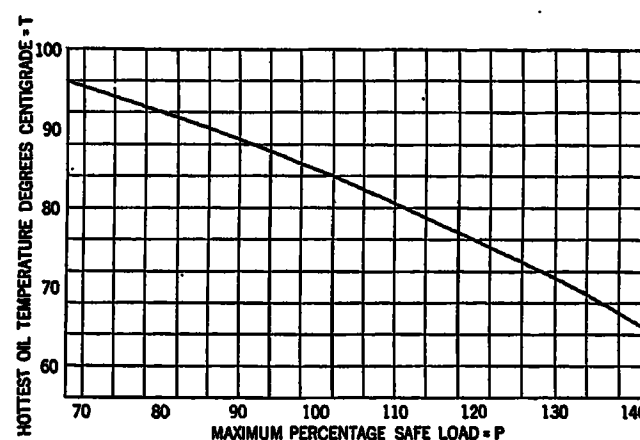


FIG. 4

The curve also shows up the possible danger of oil temperature alarm protection. Suppose in the example the oil thermometer were set to operate an alarm when the hottest oil temperature exceeded 80 deg. cent. Curve 4 shows that the alarm would be given quite unnecessarily so long as the load were below 112 per cent. On the other hand, the transformer might be carrying a load greater than 112 per cent and greater than the maximum safe limit (*i. e.*, with a hottest spot greater than 105) without the alarm functioning.

In some countries it is common for oil alarms to be set at 90 deg. cent. In the example referred to, representing an average oil-immersed self-cooled transformer, if the air temperature were 30 deg. cent. and the transformer were overloaded 20 per cent continuously, the hottest oil rise would be 58.2 deg. cent. and the hottest oil temperature 88.2 deg. cent. The alarm would, therefore, not function although the hottest spot temperature would be 117 deg. cent. and the transformer loaded beyond the safe limit.

These illustrations show the numerous practical uses of a curve such as Fig. 4.

TRANSFORMER SAFE LOAD INDICATOR

It has been shown that the hottest oil temperature is misleading as a guide to the safe loading of a transformer and that the true criterion is the hottest spot temperature within the windings. Instruments have been developed in various forms by many transformer

2. "Thermal Rating of Transformers," *I. E. E. Journal*, (England), Vol. 66, No. 380, p. 841.

manufacturers for measuring indirectly this hottest spot temperature.

In principle, the components T and G from Equation (1) are measured separately. T is measured directly and G is obtained indirectly through the relation between it and the load current in the windings. A current transformer is therefore necessary and may be connected on either primary or secondary side of the main transformer.

Such instruments show clearly whether the transformer is fully loaded and will actuate an alarm or close a relay tripping circuit when a dangerous condition is being approached.

By calibrating an instrument of this type in percentage of maximum safe load instead of in hottest spot temperature, the information given by the curve Fig. 4, and illustrated by the examples previously described, can be indicated directly. Inspection of Equation (10) shows that the variable factors are P , the load on the transformer, and T , the hottest oil temperature, both of which are already used in the hottest spot temperature indicator.

With this calibration the instrument shows directly:

1. The existing load as a percentage of the maximum safe load—showing how much of the permissible output rating is being utilized.

2. The maximum load on the transformer during any desired period expressed as a percentage of the maximum safe loading. If, for instance, this record were 75 per cent over a period of 24 hr., it would mean that at no time during that period did the load on the transformer exceed 75 per cent of its available capacity.

The formula assumes that when any given load is switched on, the winding temperature difference G reaches the value corresponding to that load immediately. This assumption underestimates the overload capacity of the transformer by a few minutes' duration of load. This is a desirable characteristic in that for rapid and dangerous increases in load, warning will be given a short time before the danger point is actually reached.

Earlier in this paper reference was made to certain approximations and assumptions necessary in applying the formulas previously developed to practical cases. Equation (10), used as the basis for the operation of the safe load indicator, is the simplest. The only thermal relation assumed is that the difference between the hottest oil temperature and the hottest spot temperature varies as the square of the load.

Departures in practise from this relation such as those caused by the effect of temperature on the losses and on the viscosity of the oil, can be eliminated by adjusting the value of G and the exponent in the formula, and by suitably choosing the position of the oil thermometer. In this way the instrument can be made sufficiently accurate for all practical purposes for use with any given transformer of reasonably normal design.

Since the standard rating of a transformer is based on continuous loading and on an abnormally high cooling medium temperature, the true rating under the normal operating conditions of discontinuous loading and comparatively low cooling medium temperature will be considerably greater than the standard rating.

By means of the safe load indicator, the true thermal rating under operating conditions may be fully utilized, and a corresponding saving made in capital cost of transformer plant installed and in exciting kv-a. and losses.

Discussion

F. F. Brand: Mr. Norris in his paper has seemed to indicate that hot-spot measuring devices are an impractical means for the operation of transformers in service. At least, as regards large transformers built in this country that is not true, because there has been a large number of transformers with hot-spot indicators in them, operating in service for some years. Perhaps it is not true to say that these are hot-spot indicators, because a spot has no area, but as a matter of fact there are devices which will indicate correctly the hottest coil and the hottest turn in that coil. Therefore, they approximate very closely a true hot-spot indicator, and these and other devices simulating the hot-spot indicator have been in service quite a number of years, so that there are quite practical devices for an operating guide in service.

Furthermore, Mr. Norris seems to indicate that the A. I. E. E. rules are very conservative in the rating of the apparatus. It may be so in very large transformers which are equipped with means to prevent oxidization of the oil, though I doubt it, but at least as regards smaller transformers, it is very questionable in my mind if it is permissible to overload small transformers without running into danger of sludging the oil and, therefore, getting a very short life.

It has been our practise in this country to recommend that even large transformers be not operated at a hot-spot temperature of 105 deg., because we have thought it more desirable to operate such transformers more conservatively and to obtain longer life of the insulation and of the oil.

There is one other point in Mr. Norris' paper to which I should like to take exception. He speaks about the temperature rise of conductors in oil which are parallel to the oil flow. Perhaps that is hardly a practical question, because no transformer has the oil flow parallel to the conductors throughout the whole length of the conductor. Mr. Norris' statement neglects two very important features of a transformer. He speaks about the high conductivity of the copper in contrast to the lower conductivity of the oil, and he has neglected entirely the surface drop from the conductor or from the insulation on the conductor through that little stagnant film of oil, which is so hard to sweep away, and he has neglected, too, the thermal drop through the insulation, and those things far outweigh the question of whether the conductivity of the copper is such as to change the distribution of the temperature gradient, and tests show this to be so.

W. F. Dawson: If I understand Mr. Norris' paper correctly, it makes proposals whereby the customer may check up the performance of his transformer and possibly increase its rating. I wish to head off any possibility of encouraging such a practise on turbine alternators. It would be exceedingly dangerous to suggest that because some margin is found between the guaranteed total temperature and that observed, increased ratings or overloads can be tolerated. Except on special contract, practically all turbine alternators are today sold on the basis of "maximum rating" which means that neither armature current nor field current is to be overloaded, except momentarily. Both

armature currents and field currents are now generally stamped upon the nameplate.

It will often be found that although the Institute rules permit an observed temperature rise as indicated by resistance of 90 deg. cent. on the field windings as compared with an observed temperature rise by temperature detectors of 80 deg. cent. with class B insulation and 60 deg. cent. with class A insulation on armature windings, there is more margin in the heating of the armature coils than in the fields. This makes it particularly dangerous to attempt overloading the armature windings simply because there appears to be a slight margin in the heating. There has been a recent tendency to place recording thermometers or temperature alarms in the path of the ventilating air. Devices of this sort are poor substitutes for the temperature indicators connected to the temperature detectors embedded in the armature windings. Usually the ammeters in armature and field circuits are a much safer guide.

A typical distribution of full-load losses in a medium-size turbine alternator, say 3000 kw., would be approximately as follows: Windage and fan loss 1.25 per cent; core loss 1 to 1.25 per cent; $I^2 R$ armature 0.5 to 0.67 per cent; load loss 0.5 to 0.67 per cent; $I^2 R$ field and rheostat 0.6 to 0.8 per cent, a total of about 4.5 per cent as compared with fixed no-load losses of about 2.7 per cent.

These data ought to show how useless thermometers placed in the outlet air stream are as indicators of the temperature of the windings.

W. M. Dann: Mr. Norris makes the point in his paper that the American Institute rules are very conservative, as Mr. Brand has already said. He says this because the standards involve continuous loading and a temperature of 40 deg. for the cooling medium, two conditions that are not met with every day in actual service.

He makes the point, which I think is really not a very serious one, that this gives to the unskilled or unscrupulous manufacturer the undesirable opportunity to design transformers that meet the Institute standards but are still of bad design. The only way in which a manufacturer could produce such a design would be to distort the use of his materials and of his cooling system quite considerably from the prevailing American practise.

An average copper temperature that would keep within the Institute figure of 55 deg. might be produced with a distorted design and it might be that the hot-spot temperatures would be excessive. I really doubt very much, though, whether any manufacturer would produce such a design because it wouldn't be worth while. The life of a transformer would be much shorter than is the actual case in service.

The point is made again that the conservatism of the American Institute rules produces a situation where transformers much larger than necessary are being installed. It seems to me that most users of transformers are satisfied with the conservatism of the Institute rules, because it must be a pretty comfortable feeling to know that with a device as important as a transformer, one has a little excess capacity under ordinary conditions of operation for emergencies and peak loads. For this reason I think it might be well to say that there are many American engineers who are satisfied that the Institute rules are not unduly conservative.

The safe loading of transformers has been receiving a lot of attention in this country in the past year or two. It is well known that a bank of transformers has an excess capacity when the temperature of the cooling medium is low, and it seems logical to take advantage of that capacity under those conditions. The logic and the reasonableness of this position are being recognized by the Institute. Recommendations for the safe loading of the transformers have been prepared and have been published for criticism, and it is not unlikely that they may be officially issued some of these days.

I am sorry that the description of the safe load indicator is not gone into a little more fully in Mr. Norris' paper. Mr. Brand has said that winding-temperature indicators are being regularly furnished by several American manufacturers, and that is the case. It appears to me from the brief description of this indicator in Mr. Norris' paper that it is practically the same device that is being used rather extensively in this country to indicate the hottest-spot winding temperature, the chief difference, it seems to me, being that Mr. Norris' instrument is calibrating in terms of load instead of temperature.

V. M. Montsinger: This paper deals with a subject which has been under discussion by one of the A. I. E. E. committees for the past three years. I refer to the subject of loading transformers by temperature instead of by nameplate rating.

There are two points which I shall discuss, (1) the methods or formulas used in determining the overload capacity of a transformer and (2) the question of what is a safe load.

This paper is devoted almost entirely to the first point but does not discuss the second point which I consider a very important one.

The formula given in Mr. Norris' paper recognizes the basic difference between the design of oil immersed apparatus and air cooled apparatus in that in the former in calculating the temperature rise it is necessary to deal with two separate and independent rises; namely, the oil rise over the ambient and the winding rise over the oil. In other types of apparatus such as generators, where the windings are embedded in core slots the thermal conditions are not so simple.

Several years ago I found that practically every heating curve obtained by tests could be expressed by the simple formula—

$$\theta = C L^n$$

θ = temperature rise.

C = constant.

L = loss.

n = some value less than unity for natural cooling and unity for artificial or forced cooling.

I note that Mr. Norris has assumed that in all cases the value of n is unity in his calculations, although he properly points out that in some cases it is less than unity.

For self-cooled transformers the oil rise varies as the total loss raised to the 0.8 power. The temperature rise of horizontal windings also varies as the copper loss raised to the 0.8 power. For vertical windings the power is more nearly unity. For water-cooled transformers, which are very popular in this country, I would point out that with a given rise in the cooling water of, say, 10 deg. cent., the oil rise varies as the square root of the total losses, i. e., $n = 0.5$. For this class of transformers the formula based on the temperature rise being proportional to the loss should not be used because the results do not check even approximately. The winding rise over the oil follows the same laws as for self-cooled transformers. The following tabulation gives the difference in temperatures calculating the rises for 125 and 150 per cent loads where the transformer has a ratio of copper to iron losses of 1:1 and 2:1 at 100 per cent load.

These figures show that while the results may be close enough for practical purposes to assume that the rise is proportional to the loss within reasonable variation of load of self-cooled transformers, but for water-cooled transformers the difference is too great to neglect. In all cases, however, I prefer to use the more exact formula because it is simple and involves very little labor. This will be discussed more in detail in my forthcoming paper.

I shall have to take exception to the statement that for long vertical coils on account of the thermal conductivity of copper being 2000 times as great as insulation, the temperature of the windings will be constant in the direction parallel to the flow of oil. Accepting this figure of thermal conductivity as correct, neither tests nor calculations bear out this statement. A few years ago I made temperature exploration tests by means of

TABLE I
COMPARISON OF KV-A. VS. TEMPERATURE RISE OF OIL AND
WINDINGS BASED ON TEMPERATURE RISE BEING (1)
NOT PROPORTIONAL TO LOSS, (2) PROPORTIONAL TO
LOSS

Self-cooled							
% load	Oil rise over ambient		Hot spot rise over				
			Oil		Ambient		
	$n_o=0.8$	$n_o=1$	$n_c=0.8$	$n_c=1$	$n_o=0.8$ $n_c=0.8$	$n_o=1$ $n_c=1$	Difference
100	45	45	20	20	65	65	0
A* 125	55	57.5	28.6	31.2	83.6	88.7	5.1
150	66.4	73.3	38.3	45.0	104.7	118.3	13.6
100	45	45	20	20	65	65	0
125	58	61.8	28.6	31.2	86.6	93	6.4
B† 150	73	82.5	38.3	45.0	111.3	127.5	16.2

Water-cooled							
% load	Oil rise over ambient		Hot spot rise over				
			Oil		Ambient		
	$n_o=0.5$	$n_o=1$	$n_c=0.8$	$n_c=1$	$n_o=0.5$ $n_c=0.8$	$n_o=1$ $n_c=1$	Difference
100	35	35	30	30	65	65	0
A 125	39.6	45	43	46.8	82.6	91.8	9.2
150	44.5	56.5	57.4	67.5	101.4	124	22.6
100	35	35	30	30	65	65	0
B 125	41	48	43	46.8	84	94.8	10.8
150	47.3	64	57.4	67.5	104.7	131.5	26.8

A* is for 1:1 ratio of copper to core loss at 100 per cent load.

B† is for 2:1 ratio of copper to core loss respectively.

thermocouples on a shell-type coil 60 in. in height and found that after conditions became constant and holding a copper density of 2000 amperes per sq. in., the temperature gradient was a straight line with a difference of 16.2 deg. between extreme lower and extreme top. This difference in temperature is checked very closely by calculations using a formula similar to that used on calculating the characteristics of transmission lines. Two thousand amperes per sq. in. represent perhaps the very maximum that is used in America today at rated load but may easily be reached on overloads now permitted in low ambients.

I note that the curve in Fig. 3 giving the maximum percentage safe load versus ambient air temperature, checks rather closely what I have always termed the 1 per cent rule; namely, that the capacity of a transformer can be increased 1 per cent for each degree by which the ambient is decreased below its standard. It is true that Mr. Norris' curve does not quite meet this but if he had made the calculations on the basis that the temperature rise varies as the 0.8 power instead of the first power of the loss, it would easily have met this rule.

I wish now to discuss a phase of this question of loading transformers by temperature which I consider much more important than the use of certain formulas because if you use the right formula you know pretty well what you are about, but for this other phase no standard formula is available and we must be guided by general experience. I refer to the question of what is a safe load when the maximum temperature is maintained continuously by means of overloads employed in connection with the use of temperature-indicating devices. I note that the author has taken 105 deg. as the maximum temperature at which it is safe to load a transformer continuously. The majority of engineers in America in the absence of experience in operating transformers under this new condition, are not willing to subscribe to, (and in fact it is not logical to set up) the same maximum temperature limit for a condition where this limit can be maintained 365 days in the year by means of overloads as for

a condition in which this same limit is reached only when several factors occur simultaneously and continuously under unusual service conditions. I mean that this value is not reached unless the following four conditions occur simultaneously:

- (1)—40 deg. ambient.
- (2)—rated load.
- (3) tested rise 55 deg. by resistance.
- (4)—maximum conventional allowance for hot spot of 10 deg. cent.

On the other hand, if a transformer is loaded by temperature rather than nameplate rating it is obvious that a condition can be brought about that is equivalent to these four conditions occurring simultaneously. The question comes up as to what temperature limit is safe for this new condition. The opinion in this country has pretty well crystallized in favor of setting up a temperature differential of at least 10 deg. as a safe limit for the two conditions of loading. In other words, we believe that if 105 deg. is a safe limit where the load does not exceed nameplate rating and the chances are very small of obtaining this limit continuously, we should not exceed 95 deg. hot spot or 85 deg. by resistance when the maximum temperature is maintained continuously with the aid of temperature indicating devices, etc. On the other hand, we are willing to admit that if it is proved that 105 deg. is a safe temperature for continuous operation it would be safe to reach 115 deg. periodically as might happen under usual service conditions and where name plate rating is never exceeded. Before subscribing to this, however, we prefer to obtain further experience under actual service conditions because, as pointed out above, this proposed method of loading is entirely new and introduces new factors which may have a very important bearing on the life of the insulations.

In order that the title of the author's paper *Safe Loading of Oil-Immersed Transformers* might not be misleading to some who are not keeping up-to-date with the progress of the art, I would point out that as I interpret the title it means "safe" in so far as the load will not cause a temperature in excess of the limits set forth. To this I heartily agree. I cannot agree, however, that it is necessarily safe from the standpoint of the life of the apparatus to maintain continuously the temperature limit of 105 deg. It is hoped that within the next year or two the A. I. E. E. can officially standardize the rules which have been prepared and published¹ for the operation of transformers by temperature. If this is done and the proposed limits are adopted it would mean that the values given in this paper should be revised in order to conform in temperature limits with our own practise.

I regret that the author has not given us a few more details as to the construction of the temperature indicator to which he refers in the last part of the paper. While this is not necessary to understand the thermal conditions in a transformer it would have added to the interest of the subject.

I might point out that the General Electric Company has been supplying for the past eleven years a temperature indicator that shows the approximate hottest spot of the winding under loaded conditions. This I believe was the first general application of a transformer temperature indicator. Full particulars on this device are given in the *General Electric Review*, June 1918.

F. D. Newbury: I wish to discuss the paper briefly from the general standpoint of standards. Mr. Norris has wisely drawn a distinction between standards for rating and, let us say, recommendations for operation. The discussion shows that there is some difference of opinion as to the conservative nature of the Institute rules. My own opinion is that we don't know whether they are conservative or not because there is no way of finding out just what the facts are.

If we take insulating materials and make laboratory tests and judge deterioration by reduction in mechanical strength,

1. A. I. E. E. JOURNAL, August 1928.

a very good case for a much lower temperature limit can be made.

If we assume that the limiting temperatures of the A. I. E. E. Standards are safe, then we must admit that practise is conservative because apparatus is rarely operated continuously under conditions of 40 deg. air temperature and up to the permissible limiting temperature rise.

However, we must face the fact that our only reliable "benchmark" is general experience. We know that we are not having undue trouble with our apparatus *as operated*. How much margin of safety exists we can only find by further experience. We cannot, therefore, change operating practise in a way that will increase the general average of operating temperature without careful consideration. Conservatism would lead to some reduction of present A. I. E. E. limits, as has been proposed by American engineers in connection with the recommendations for operation of transformers by total temperature.

In the application of this principle of operation by total temperature, there are two difficulties. I have already mentioned the first one, that is, whether our present standards can be applied in practise up to their full limit or not. The second is that no hot-spot indicator really measures the actual hot-spot temperature.

Some rather complete tests in the case of turbine alternators have shown that there is anywhere from 5 to 20 deg. difference between the actual hot-spot copper temperature and the highest temperature that can be measured by conveniently located hot-spot indicators. So we have that thermal difference to deal with in applying this principle of operation by total temperature. The difference between actual hot-spot temperature and measured hot-spot temperature increases as loads above the rated load are applied. So the increase in load above the rated load involves this additional unknown factor and another factor of safety must be applied in the application of this method of loading.

A. B. Cooper: I think that although this paper was written as of two years ago, in all probability Mr. Norris would have no occasion to change his opinion on the details of the paper based on more recent practise or experience. Mr. Brand has pointed out that in his estimation the remark regarding the conservatism of the A. I. E. E. rules applies to large transformers but not particularly to moderate capacity transformers. Mr. Norris has in mind, I think, in preparing this paper, more the larger types of transformers. His company is building at the present time transformers of unit capacity of 75,000 kv-a., and in that case, if a 20 per cent margin is available under the conditions as outlined, due to variation in temperature, he is dealing with a capacity of 15,000 kv-a., which may be idle capacity or waste capacity in his transformer.

Mr. Brand pointed out that transformers have been in service for a very long time with embedded temperature detectors. Mr. Dawson answered that point very satisfactorily when he said a moment afterward that "temperature detectors are dangerous." Mr. Dann's comment has taken exception to what Mr. Norris said in regard to the variation in thermal gradient of transformers, particularly in reference to transformer design on this side of the water. My own feeling is that as between manufacturers, as between different types of design, or even as between designs put out by the same manufacturer, variations exist in the temperature gradient, of the order of 40 to 50 per cent.

Mr. Montsinger has commented on the temperature variations which result from departing from unity in the exponential value in the formula. Mr. Norris has used unity for simplicity; that is of course for simplicity in presentation of his paper, and he has not, I am sure, considered developing his temperature indicator on the basis of unity exponential value only.

E. T. Norris: Many of the discussors have commented on the subject of whether it is safe to run transformer insulation continuously at the national standard limit temperature of 105 deg. cent., and have assumed that such a temperature is recom-

mended in the paper. I am glad, therefore, that Mr. Montsinger has pointed out that the paper does not discuss at all the question of what is a safe hottest-spot temperature.

In the beginning of the paper the hottest-spot temperature is defined as the maximum temperature the insulation will safely withstand. The method of predetermining the safe loading and the use of the safe-load indicator depend upon the selection of a hottest-spot temperature in accordance with this definition.

As regards the actual value of the hottest-spot temperature, Messrs. Montsinger and Newbury have summarized the position excellently. My own view is, perhaps, rather more optimistic. All transformer manufacturers of many years' standing will have collected definite experience of the safe hottest-spot temperature for the insulation they have used. Developments in the manufacture and treatment of insulation tend to raise this temperature rather than lower it, so that such experience may safely be used.

Again, suppose *A* to be the average loading conditions of a transformer. Very many transformers everywhere are operating safely under loading conditions *B*, considerably worse than the average *A*, though still below the A. I. E. E. standard rating conditions. When operating transformers by temperature, the general average can at least be raised from *A* to *B* without any risk. This argument refers to Mr. Newbury's statement that operating practise should not be changed in a way that will increase the general average of operating temperature without careful consideration.

The discussion of the actual value of hottest-spot temperature for standardization purposes is irrelevant in connection with the present paper, as the problem does not arise. The information given to the operating engineer is the proportion of the maximum safe output of a transformer actually being used at any time.

In calibrating the instrument the manufacturer uses a hottest-spot temperature based on his knowledge of the materials he employs, and with as much margin for his safety as he likes.

The new proposal does, however, demand skilled and accurate methods of thermal design. A transformer designer must have good control over the thermal characteristics and design of his transformer to be able to view the new method of loading with approval or even with equanimity.

Many discussors have asked for more details of the safe load indicator. It is constructed on the same principle as the winding-temperature indicators referred to by Messrs. Brand, Dann, and Montsinger, the essential difference being that it is not calibrated in hottest-spot temperature. The information given by a winding-temperature indicator is somewhat negative in character. Suppose, for example, the hottest-spot temperature of a transformer at a given instant is 75 deg. cent. while the maximum safe value is 100 deg. cent. The transformer is obviously not fully loaded, but the unused capacity cannot be determined from these two temperatures, and may be any value between 10 and 35 per cent, depending on the thermal design of the transformer and the temperature of the cooling medium. The operating engineer knows, therefore, that the transformer is not fully loaded, but he does not know what the margin is, and is, therefore, unable to make full use of it.

The safe-load indicator is calibrated in percentage of maximum safe load instead of in hottest-spot temperature, and therefore shows directly just how much of the available output rating is being utilized at any time or over any period of time.

Further details of the safe-load indicator are given in the Institution of Electrical Engineers' *Journal* referred to later, and the instrument itself is illustrated in Fig. 1 herewith.

Mr. Brand considers the Institute rules are not conservative, while Mr. Dann agrees that they are, and approves of the conservatism on the grounds that it is comforting to an operator to feel that his transformer has a margin of capacity for emergency conditions.

All operating engineers will, I think, agree with Mr. Dann.

The important point is that hitherto the operator has been able merely to feel that the transformer had some margin for an emergency, whereas when the method recommended in the paper is followed, the operator will *know* that the transformer has a margin; he will *know* just how much that margin is in kv-a.,

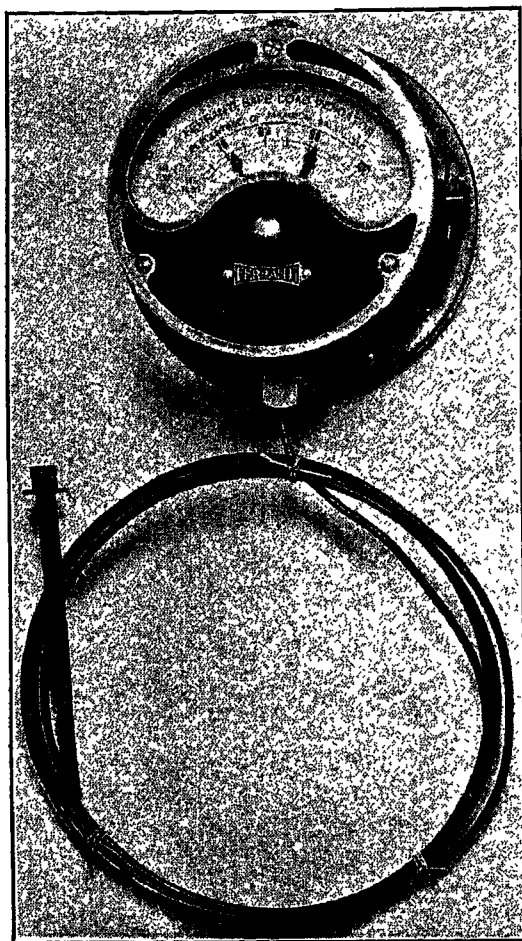


FIG. 1—SAFE-LOAD INDICATOR FOR TRANSFORMERS

and that knowledge will be automatically kept up-to-date for him and can be checked at any time.

The principles of operation by temperature are applicable to all sizes and types of transformers without restriction, and the safe-load indicator is equally valuable in every case.

Mr. Montsinger points out that the temperature rise of either windings over oil or oil over air is sometimes proportional

to something less than the first power of the watts loss, and gives tables showing the effect of the reduced exponent on the resulting temperature rises. This fact is emphasized three times in the paper.

The formulas developed in the paper were intended for purposes of illustration and exposition rather than for application to practical problems, and were therefore simplified by such means as assuming unity exponent. I pointed out, however, that the subject has been dealt with quantitatively and in detail elsewhere (Inst. Elec. Eng. *Jl.*, Vol. 66, p. 841). In that paper complete formulas have been developed in which both variations in the exponent and other complications are taken into account.

Incidentally, the analysis of the winding-temperature difference into surface drop and thermal drop through the insulation, as referred to by Mr. Brand, is also dealt with in detail. The Institute papers by Messrs. Montsinger, Luke, and Cooney were of great assistance in the preparation of both papers.

The safe-load indicator is not subject to errors such as the assumption of unity exponent, since it works on the actual oil temperature and winding-temperature difference existing in service.

In pointing out that no transformer has oil flow parallel to the conductors for the whole of the winding, Mr. Brand is quoting from the paper. Any drop in temperature along the conductor, even in the rather extreme case described by Mr. Montsinger, can be allowed for by slight adjustment of the constant K in Equation (2).

Mr. Montsinger states that if Fig. 3 had been calculated on the basis that the temperature rise varies as the 0.8 power instead of the first power of the loss, it would have closely checked the empirical 1 per cent rule. On the other hand, I find that Fig. 3, which was calculated from the approximate formulas developed in the paper, agrees almost exactly with the constant load curve given in Fig. 19 of N. E. L. A. Report No. 267-3 which was, I think, plotted from actual measurements on many typical distribution transformers.

In conclusion, the chief aim of the paper is to encourage the rating and actual loading of transformers on a true thermal basis. To this end a practical method is developed of predetermining the true thermal rating under different conditions of loading, and a practical means is described for measuring the safe load capacity of a transformer under actual service conditions.

Induction Motor Operation With Non-Sinusoidal Impressed Voltages

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and

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Synopsis.—The usual procedure in considering the operation of induction motors has been to neglect the effect of harmonics. Although in most instances this gives results which are sufficiently accurate, the question of how much these effects are or how much is being neglected has yet to be answered in electrical engineering literature. In this paper an attempt is made to answer this question. It is also devoted largely to a statement of results with only such ex-

planation as space permits. The conclusions are that, with harmonics of 10 per cent or less, the harmonics produce an insignificant effect, for all types of induction motors and for all conditions of operation, except for the no-load condition. In this case, significant but not serious increases of I^2X occur. Also lightly loaded induction motors may be counted on to smooth out the impressed electromotive force wave.

THERE are two types of harmonics that may be present in induction motor operation, (a) time harmonics introduced by the impressed e. m. f. and (b) space harmonics introduced by the counter e. m. f. of the motor. The object of study in this paper is the former type of harmonics.

In order to visualize what happens in the case where the impressed e. m. f. contains one harmonic, it is convenient to think of an induction motor as consisting of two motors identical with the motor under consideration, with shafts connected and drawing power, one from the fundamental e. m. f. source and the other from the harmonic e. m. f. source. The reactance of the harmonic motor will be n times that of the fundamental motor, where n is the order of the harmonic. The resistance of the harmonic motor as indicated by our tests will be greater than that of the fundamental motor, although not n times as great. One author² claims the resistance of the harmonic motor to be the same as that of the fundamental motor. When this pair of motors is operating under any ordinary load, the slip is close to zero per cent for the fundamental motor, while for the harmonic motor it is a very large per cent, 133 1/3 per cent for the third harmonic in the two-phase motor, 120 per cent for the fifth harmonic in the three-phase motor, and 85 5/7 per cent for the seventh harmonic in the three-phase motor. For example, if 1800 rev. per min. is synchronous speed for the two-phase fundamental motor, $3 \times 1800 = 5400$ rev. per min. in the opposite direction is synchronous speed for the third-harmonic machine. The slip is therefore 7200 rev. per min. or $7200/5400 \times 100 = 133 \frac{1}{3}$ per cent. In the case of the seventh harmonic and the three-phase motor, $7 \times 1800 = 12,600$ rev. per min. in the same direction as synchronous speed, and the slip is therefore $(12,600 - 1800) \times 100 \div 12,600 = 85 \frac{5}{7}$ per cent. When a pure sine wave is impressed on the

motor, 100 per cent voltage is considered to be impressed on the motor of fundamental frequency and 0 per cent on the harmonic motor. When a non-sinusoidal voltage of 100 per cent effective value is impressed on the motor, if the harmonic be 25 per cent of the fundamental, the fundamental motor will have impressed on it a 97 per cent voltage. Considering a given effective voltage, this voltage can be produced either by 100 per cent fundamental and 0 harmonic or with $100 \div \sqrt{1 + H^2}$ per cent fundamental and $H \times 100 \div \sqrt{1 + H^2}$ per cent harmonic, where H is a fraction, 0.25 for example in the above cited case. Thus, $H \times 100 \div \sqrt{1 + H^2}$ per cent voltage will be impressed on the harmonic motor and $100 \div \sqrt{1 + H^2}$ per cent on the fundamental motor. With non-sinusoidal operation, the fundamental machine will receive a decreased voltage and function as an ordinary induction motor functions with decreased voltage. The harmonic machine operating with a large slip will take currents, active and reactive watts, practically the same as if its rotor were blocked. The harmonic motor acts more or less as a harmless parasite on the fundamental motor, neither helping nor hindering the operation of the fundamental motor to any considerable degree. Its braking effect is entirely negligible so long as the harmonics are kept below 10 per cent. Its main disadvantage is that it prevents the fundamental motor from getting its full 100 per cent voltage and that it absorbs from the line a moderate amount of active and reactive power for which it does no good in return.

Coming now to practical operating conditions, the outstanding fact is that with a 10 per cent harmonic, the largest harmonic allowable by the A. I. E. E. Standards Rules, the quantity $100 \div \sqrt{1 + H^2}$ becomes 99.5 per cent, only half of one per cent loss in voltage impressed on the fundamental motor. Therefore the fundamental motor will have no more than a one per cent decrease in torque and horsepower. With a 10 per cent harmonic, the active and reactive watts taken by the harmonic motor are a small percentage of the total active and reactive watts for all conditions of operation

1. Pennsylvania State College, State College, Pa.

2. Arnold, Vol. 5, Part I, p. 194, *Die Asynchronen Wechselstrommaschinen die Inductionmaschinen*.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

except light loads. The braking or accelerating torque of the harmonic motor is a small fraction of one per cent of the fundamental motor torque.

ANALYTICAL TREATMENT

As suggested in the introduction, it is helpful to replace the motor under consideration by two motors, shaft-connected, and each identical with the original motor. Each of these motors will have its own equivalent circuit and its proper impressed electromotive force. Solutions of these two circuits may then be made separately and the results combined. By applying this method the operation of any induction motor for any condition may be predicted. Such calculations were made by the authors for a number of motors and a variety of operating conditions. These calculations are tedious and space does not permit their reproduction here. The conclusions from these calculations are that

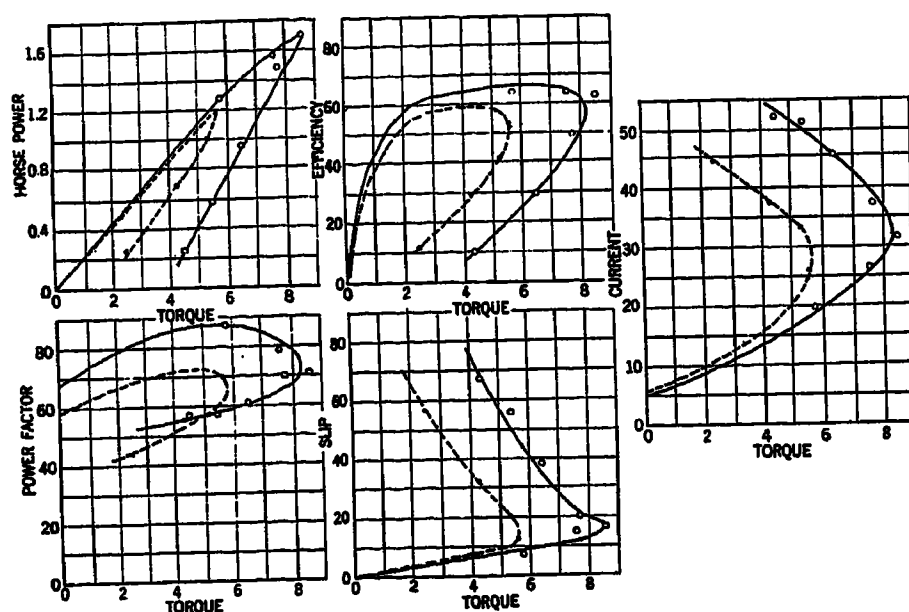


FIG. 1—TEST RESULTS OF MOTOR OPERATED ON SINUSOIDAL AND NON-SINUSOIDAL VOLTAGES

The full lines show operation on sinusoidal voltages; the dotted lines non-sinusoidal operation

so long as harmonics are kept below 10 per cent, the departure of the motor from normal performance is quite negligible except for light loads. The case of light load is treated in a later section.

In order to establish the validity of this method of calculation, a complete test was run on a small squirrel-cage motor for both sinusoidal and non-sinusoidal operation. Fig. 1 shows curves of horsepower, efficiency, power factor, current, and slip plotted against torque. The constants of the motor follow:

Name plate data:

A 5-hp., three-phase, 60-cycle, 110-volt, $26\frac{1}{2}$ -ampere, 1150-rev. per min., squirrel-cage motor.

Blocked test data:

E per phase (WYE) = $14\frac{1}{2}$ volts, I = $26\frac{1}{2}$ amperes

R per phase (cold) = 0.227

X per phase = 0.492

Running light data:

E line = $50\frac{1}{2}$ volts, I = $2.86 - j 3.14$ = 4.22

The tests were run at a voltage of $50\frac{1}{2}$, sufficiently

below rated voltage to allow the motor to be taken through its complete characteristics. To obtain these complete characteristics, the following arrangement of apparatus was used: A d-c. motor drove a harmonic alternator,³ which supplied the induction motor under test. Shaft-connected to the induction motor was an electro-dynamometer which pumped power to another d-c. machine driven by a synchronous motor. The harmonic alternator's speed was maintained at 1234 rev. per min. The actual percentage of the fifth harmonic impressed on the induction motor was measured by the "wave-shape meter"³ and was found to be 57 per cent.

It was found also that when calculations were made using the equations for the accurate equivalent circuit of the induction motor, very good agreement was had in the case of the speed-torque and horsepower-torque curves and fair agreement for the other three curves. Since beyond the breakdown point the currents are excessive and the values of primary and secondary resistance are uncertain because of heating, only a moderate agreement between observed and calculated values was obtained. For those who might care to check these calculations, the following circuit constants are supplied: R_1 (hot) = 0.13; R_2 (hot) = 0.14; X_1 = X_2 = 0.25; g_0 = 0.098; b_0 = 0.1076, volts per phase = 29.12. When operating with the 57 per cent fifth harmonic, the voltage of the fundamental reduces to 25.3 volts, while the fifth harmonic voltage becomes 14.4 volts.

While such calculations cannot be reproduced here, it may be desirable to give just two simple calculations as follows:

The maximum torque, fundamental test

$$= \frac{3 \times 2}{2 \pi 61.7} (29.12)^2 \frac{1}{2 (0.13 + \sqrt{0.13^2 + 0.5^2})} \times 0.737 = 7.5 \text{ lb-ft.}$$

The maximum torque, non-sinusoidal test

$$= 7.5 \times \left(\frac{25.3}{29.12} \right)^2 = 5.68 \text{ lb-ft.}$$

The above calculations are not based on the exact equivalent circuit and are only moderately close.

Although complete calculations have not been included, they provide the basis for the following discussion of the curves of Fig. 1.

Slip-Torque Curves. When the fifth harmonic is present, the fundamental must be reduced, in this case from 29.12 to 25.3 volts. As illustrated by the calculation, this reduces the torque in the ratio of the square of the voltages. The reduction due to the counter torque of the fifth harmonic is quite small, only about one-third of a pound-foot at breakdown. Neglecting this, it may be said that the motor acts as if operating simply with a reduced fundamental voltage.

3. A New Wave Shape Factor and Meter. Doggett, Heim, and White, A. I. E. E. TRANS., Vol. 45, 1926, pp. 435-442.

Horsepower-Torque Curves. These curves are corollary to the slip-torque curves, since

$$\text{hp.} = \frac{2 \pi \text{ Torque } (1 - S) 1234}{33,000}$$

Current-Torque Curves. Up to breakdown for any assigned torque the current with non-sinusoidal operation must be larger than the current with sinusoidal operation for two reasons: (a) The reduction in fundamental voltage calls for a larger current to give the same

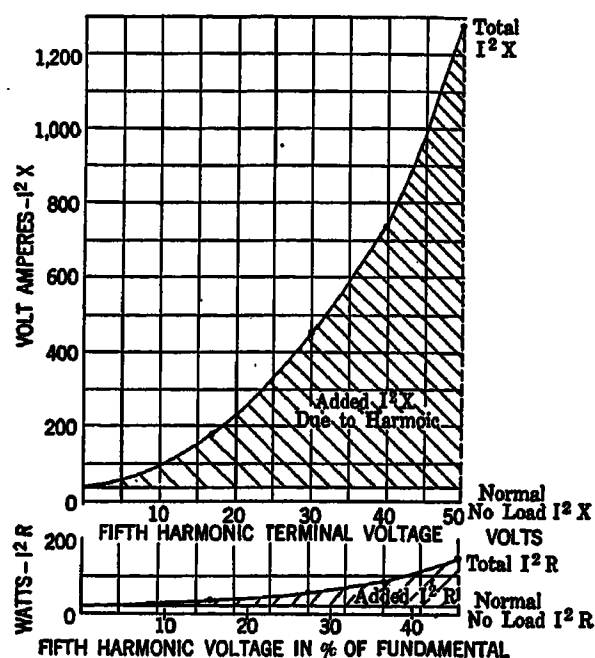


FIG. 2—TEST RESULTS AT LIGHT LOAD

Showing increase in $I^2 R$ and $I^2 X$ with increase in harmonic voltage

torque. (b) The fifth-harmonic current must be compounded with the fundamental current according to the law

$$I_{\text{total}} = \sqrt{I_1^2 + I_5^2}$$

Efficiency-Torque Curves. For any assigned torque, the extra current will result in extra copper loss and therefore less efficiency.

Power-Factor-Torque Curves. For any assigned torque, a very considerable $I^2 X$, due to $I_5^2 X_5$, will materially increase the demand for reactive power and thus reduce the power factor.

LIGHT-LOAD CONDITION

As has already been pointed out, an induction motor operating on light load with non-sinusoidal impressed voltages may be expected to show some considerable departure from normal operation. In general, the no-load copper loss, $I^2 R$, and the no load $I^2 X$ will be very much increased. Calculations show that an average three-phase motor acted upon by an e. m. f. containing an eight per cent fifth harmonic, if its percentage of reactance be as low as 10 per cent, will have its no-load copper loss multiplied by three, and its no-load $I^2 X$ multiplied by seven. In a certain rather high-reactance motor, the normal no-load $I^2 R$ was 49 and the normal no-load $I^2 X$ was 119. Due to a 10 per cent fifth harmonic, the added $I^2 R$ was 33 and the added $I^2 X$ was 60. Repeated attempts to measure this

added loss accurately proved failures, and the following test is submitted to illustrate the above claims without trying to cite an individual case of exact agreement between calculation and observation.

In this rather unusual test, the stator of a wound-rotor induction motor was connected to the fundamental terminals, while the rotor was connected to the fifth-harmonic terminals of a harmonic alternator.³ On the stator was impressed normal voltage and normal frequency continuously, while the fifth-harmonic voltage was varied from zero to 50 volts. Although tests with both directions of phase rotation of the fifth harmonic were made, the fifth-harmonic current and power data were alike in the two cases. From this test and two supplementary blocked-rotor tests, sufficient data were obtained to plot the curves of Fig. 2, which show the $I^2 R$ and $I^2 X$ plotted as a function of the per cent harmonic. In this case, a 20 per cent fifth harmonic doubles the no-load $I^2 R$ and multiplies the no-load $I^2 X$ by seven.

Although at no-load the added $I^2 X$ appears quite significant, it usually is small in comparison with the reactive power needed for the excitation of the motor. In this case, the excitation required some 1350 volt-amperes.

■ An induction motor supplied with non-sinusoidal

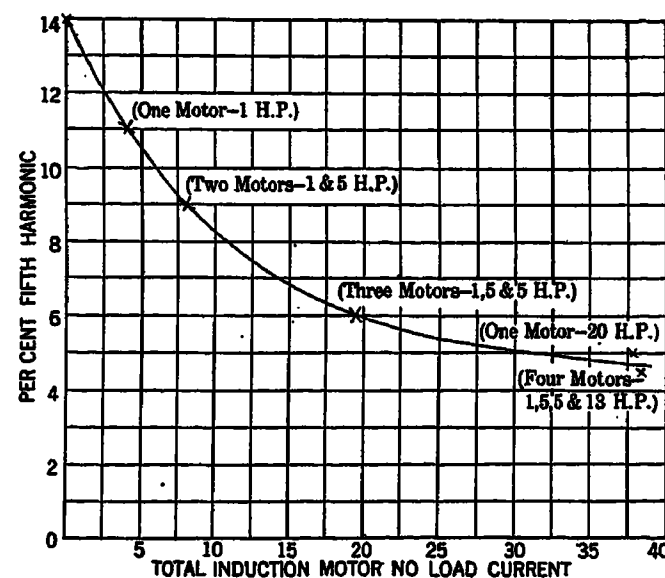


FIG. 3—CURVE SHOWING HOW HARMONIC VOLTAGE OF GENERATOR DECREASES WITH INCREASING INDUCTION-MOTOR LOAD

e. m. fs. will take from the line some additional $I^2 X$ and $I^2 R$. It will draw from the alternator harmonics of current which by internal drops will reduce the sources of non-sinusoidal e. m. fs. inherent in the alternator. Any alternator has a poorer regulation at frequencies higher than normal. To all but the fundamental frequency, the running induction motor acts practically as if blocked, i. e., slip in the neighborhood of one. Therefore, for harmonics like the fifth and seventh, the induction motor at no-load will have a lower impedance than it has for the fundamental. In such a case, the current per volt will be larger for the harmonic than for the fundamental and with a sufficiently large harmonic e. m. f. present, the harmonic current

may exceed the fundamental current. The alternator, however, has a poor regulation when operated on a harmonic. Consequently, an alternator which shows a 14 per cent fifth harmonic at no-load will show a less per cent harmonic, (that is, 5 per cent), when operating unloaded induction motors, and this is illustrated by Fig. 3. In short, induction motors have some tendency to smooth out the e. m. f. wave of the alternator which is supplying them. The results of this test were obtained by use of the wave-shape meter.

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Discussion

B. L. Robertson: Last year at Penn State we did some work on the subject of synchronous motor operation with non-sinusoidal impressed voltages. I should simply like to point out as a discussion of the paper by Doggett and Queer that in line with wave shape improvements by induction motor, the modern synchronous motor by virtue of its armaturous winding will be just as effective in improving wave shape, likewise the synchronous converter.

R. G. McCurdy: I should like to add one thought to the observations made on the effect of induction and small synchronous motors on wave shape given in this paper. They have pointed out the smoothing effect on the supply-system voltage wave shape due to the lower impedance of the induction and synchronous motors at the harmonic frequencies than at the fundamental. In addition to this effect there are the harmonics which may be added to the system due to the stator and rotor slots of these machines and due to non-sinusoidal flux distribution. The resultant effect on the wave shape of course depends upon the relative magnitudes of generator and motor harmonics and the impedances involved. My experience with measurements of wave shape on operating power system indicates that large alternators have lower harmonics than many of the smaller induction and synchronous motors connected to the system, so that the over-all tendency of this utilization apparatus is to increase somewhat the harmonics on the system rather than to decrease them as might be inferred from the data given in the paper.

E. W. Henderson: An interesting point along a line very similar to that suggested by Mr. Doggett is that of the operation of an induction motor at sub-synchronous speeds with characteristics similar to the synchronous motor. It has been customary to explain the reduction of torque and the running of an induction motor at sub-synchronous speeds as due to harmonics, the general idea being that the torque is reduced to a certain point but beyond it is increased. The usual method of indicating this on a diagram is to show the normal torque of the induction motor from starting to synchronous speed and on the same diagram indicate the torque which would be experienced due to the harmonic, these two being combined to show the dip in the torque curve.

It is interesting to note that some investigation has been carried on by Mr. Dreese of the Lincoln Electric Co. on this subject of the action of the induction motor as a synchronous motor at sub-synchronous speeds, and I understand that a paper will be presented by him at the next Winter Convention on this subject. This idea of the induction motor running as a synchronous motor at sub-synchronous speeds is a new one to me. By the use of a stroboscope, it has been noted that a motor running at sub-synchronous speeds will act identically as a synchronous motor and that when the load is increased, the angle of displacement will increase but the speed will continue to be constant. This action goes on up to the breakdown point, when of course the induction motor breaks away. Apparently in all respects, at sub-synchronous speeds, the induction motor acts exactly in a manner similar to a synchronous motor. I think that Mr. Dreese concludes that this is due to slot harmonics rather than line harmonics and I have mentioned it only because it is a case of reduced torque and is somewhat parallel to the cases cited by Mr. Doggett.

L. A. Doggett: The point made by Mr. McCurdy is true. We must consider the effect of the receiver apparatus just as well as the source apparatus and we have been studying the whole problem.

I should just like to make one point in connection with his remarks. If, due to this, receiver apparatus harmonics do get out on the line, they are all ready for correction by such induction motors as may be present; that is, the action of the induction motor is ready to function, regardless of the source of this disturbance.

In the first paragraph of the paper, we have limited our discussion to what I called time harmonics and I am interested to learn from Mr. Henderson that we shall probably get a paper which will cover this other interesting proposition of space harmonics.

Outdoor Hydrogen-Ventilated Synchronous Condensers

BY ROBERT W. WIESEMAN*

Member, A. I. E. E.

Synopsis.—Hydrogen is an excellent cooling medium for high-speed rotating electrical machinery. When it is substituted for air, a machine can be operated at a higher load with the same temperature rise and the windage loss is decreased to one-twelfth. Furthermore, since no oxidation can take place in this type of machine, the life of the insulation is increased and short circuit and corona troubles are very materially reduced. The machine is especially quiet, and it can be placed out of doors without increased expense.

The first commercial application of hydrogen cooling for electrical machinery was made on a 12,500-kv-a. outdoor synchronous condenser. Another outdoor hydrogen cooled condenser designed along these lines rated 20,000 kv-a., is also in operation. Both condensers were placed in service in 1928 and their performance has been very satisfactory. This paper describes the construction of the machines and reviews the advantages and disadvantages of hydrogen cooling.

I. INTRODUCTION

Advantages in Ventilating a Machine with Hydrogen

THE characteristics of hydrogen gas, which make it desirable as a cooling medium for high-speed rotating electrical machinery, are as follows:

Low Density of Hydrogen. Hydrogen is a colorless, odorless, tasteless gas whose density is only 7 per cent that of air. The windage loss of a rotor is approximately proportional to the density of the gas in which it rotates. Thus, the windage loss of a rotor running in an atmosphere of pure hydrogen is only 7 per cent of the air loss. It was found to be entirely practical to maintain a gas mixture in a machine of 99 per cent hydrogen and 1 per cent air, etc., and so a windage loss of only 8 per cent of the air loss is realized. The decreased windage loss also decreases the amount of heat to be removed from the machine, and the size of the surface cooler can be reduced when hydrogen is used as a cooling medium. The bearing friction loss is the same in hydrogen as in air.

High Thermal Conductivity of Hydrogen. Hydrogen conducts heat about seven times better than air and the specific heat of a gram of hydrogen is about 14.5 times that of a gram of air. Consequently, heat passes across the small spaces in the insulation and between the laminations, etc., much more readily than with air cooling; and so the internal copper temperature, for a given surface temperature, is less in hydrogen than in air.

High Forced Heat Convection of Hydrogen. In an atmosphere of hydrogen 30 per cent more heat can be transferred from heated surfaces than in air with the same surface temperature drop. Furthermore, when the hydrogen comes in contact with a surface cooler, more heat can be transferred to the cooler than with air. This again enables a smaller surface cooler to be used; or with the same cooler a lower cooling medium temperature is realized, and the internal temperature of the coil is still further reduced. The bearing temperature is also less in hydrogen than in air.

The reduction of windage loss, the increased thermal conductivity, and forced heat convection of hydrogen result in an increased output of 25 per cent or more, depending upon the hydrogen pressure used, the type of ventilation employed, the degree of saturation in the magnetic structure, and the stability required.

No Combustion Possible in an Atmosphere of Hydrogen. There is no oxygen or dirt present in the machine, and, consequently, a combustion cannot take place. This eliminates the need of fire extinguishing apparatus. The burning of iron and insulation following a ground or short circuit is reduced to a minimum. The insulation retains its flexibility, and its life, therefore, is greatly increased. The bearing lubricating oil remains clean and it does not oxidize or sludge so readily as in an air cooled machine.

Detrimental Effect of Corona Reduced to a Minimum. The thickness of the armature coil insulation is governed partly by the high-voltage gradient and the formation of corona in the minute spaces of the insulation. Tests have demonstrated that the damage caused by corona is practically absent¹ in an atmosphere of hydrogen. Not only will this increase the insulation life, but it will allow a thinner insulation to be used or a greater factor of safety to be secured. These factors will not only make it easier to build machines of present day voltages, but they will make it possible to employ higher voltages in the future. A 24,000-volt, 15,000-kv-a. hydrogen-ventilated synchronous condenser, now under construction, gives evidence of this trend.

Finally, the absence of corona damage to varnished fabric insulations will permit their use on high-voltage machines with a substantial decrease in cost. The greater impulse voltage strength of varnished fabric as compared to mica insulation thus gives the hydrogen cooled machine a further advantage for installations where high-voltage surges are likely to be experienced.

Outdoor Operation. At practically no increase in cost a hydrogen-ventilated machine can be made suitably weather-proof for outdoor operation. This effects a great saving in building expense.

Quiet Operation. The windage noise of a totally

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Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

1. For references, see Bibliography.

enclosed hydrogen cooled machine is very much less than that of an air cooled machine. Thus, a hydrogen-cooled machine is exceptionally quiet and it can be placed outdoors in a residential district where a noisy machine would be very objectionable.

Disadvantages in Ventilating with Hydrogen

Safety Precautions. When hydrogen cooling was first proposed, some difficulty in preventing accidental explosions was anticipated. The increasing familiarity with the problem and the extensive use of hydrogen for many industrial purposes such as brazing, annealing, welding, etc., indicate that there should be no difficulty with this problem. The Schenectady factory of the General Electric Company uses 30,000,000 cu. ft. of hydrogen per year without experiencing any difficulty from this source. Every city has one or more gasometers containing many thousands of cubic feet of gas which, though not explosion-proof, give practically no trouble. The following table gives the stored energy in a steam boiler, in a large turbine-generator rotor, and in the gas of a hydrogen-ventilated synchronous condenser when it contains the most explosive mixture of air and hydrogen.

	Stored energy ft.-lb.	Per cent
Steam boiler		
2000 boiler hp.....	5000×10^6	100
Large turbine-generator rotor.....	300×10^6	6.0
Hydrogen-ventilated machine containing 1000 cu. ft. of the most explosive mixture of air and hydrogen at atmospheric pressure..	70×10^6	1.4

It is quite evident that a hydrogen-ventilated synchronous condenser has very much less potential explosive force than other apparatus in common use.

A mixture of hydrogen and air will not explode if the hydrogen content, by volume, is more than 70 per cent or less than 10 per cent. If a machine is scavenged with carbon dioxide before it is filled with hydrogen, no explosion can take place when it is started for the first time. The hydrogen pressure in the machine is automatically maintained slightly above atmospheric pressure. This prevents air from leaking into the machine, and eventually the hydrogen purity will reach that of commercial hydrogen which is usually around 99 per cent. It has been found that a hydrogen purity of 98 per cent can be obtained in a few hours after a machine is filled with hydrogen. A hydrogen purity indicator can be made to ring an alarm if the purity falls below normal. A fan pressure gage calibrated to read hydrogen purity gives an instantaneous reading of the hydrogen purity in the machine when it is in operation. Thus, the possibility of an explosion is very remote if the machine is given ordinary supervision.

Increased Disassembly Expense. If a hydrogen-ventilated condenser must be disassembled for repairs, more time will be consumed and more expense will be

involved than with a standard air-cooled machine. On the other hand, it should not be necessary to dismantle the hydrogen-ventilated machine so often because of its longer insulation life, its lower bearing and internal coil temperature, and the absence of dirt. It is believed, therefore, that the total maintenance expense over a period of years will be less for the hydrogen-cooled machine.

Increased Number of Auxiliaries. As with any automatic or remotely controlled electrical equipment, so with a hydrogen-cooled machine a number of auxiliary devices is necessary. These devices consist of an automatic hydrogen pressure control, a hydrogen purity indicator, thermometers with alarm attachments, water coolers, and the control for the motor-driven exciter set. The accessories, however, have been found to be reliable on other apparatus and since they do not represent a very large addition to the usual amount of accessories, it is believed that they will operate satisfactorily.

II. HYDROGEN COOLING CAN BE EASILY APPLIED TO A SYNCHRONOUS CONDENSER

It is unnecessary to have the shaft of a condenser extend through the gas-tight shell as in the case of a turbine generator, and so a seal² of any kind around the shaft is not required. With this arrangement, the construction of the machine is simplified because the entire machine, including the bearings and shaft, can be enclosed in a gas-tight shell.

III. DESCRIPTION OF OUTDOOR INSTALLATION

Fig. 1 shows the 12,500-kv-a. hydrogen-ventilated synchronous condenser completely installed at the Pawtucket, R. I. Substation of the New England Power

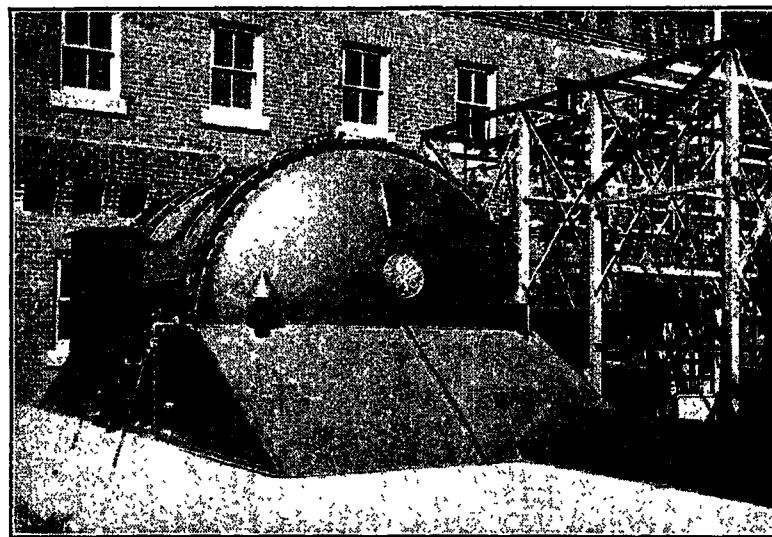


FIG. 1—THE FIRST OUTDOOR HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER, 12,500-KV-A., 900-REV. PER MIN., THREE-PHASE, 60-CYCLE, 13,800-VOLTS. NEW ENGLAND POWER CO., PAWTUCKET, R. I.

Company. This condenser is the first of its kind ever built. It is located out of doors without any protection from the weather, but is placed over a pit which is made weather-proof by a substantial sheet-iron covering. Along side of the condenser are located the switches, starting compensator, transformers, and lightning ar-

resters. Fig. 2 shows this condenser with the end head removed and Fig. 3 a sectional view of the machine. These views show the semi-circular surface coolers, the bearing housing and its fabricated support, the high-voltage armature terminals, the collector housing, and the construction of the gas-tight frame. The bearings

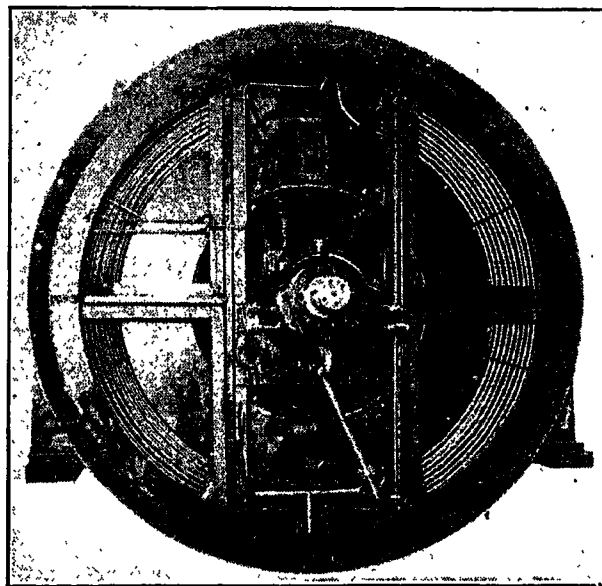


FIG. 2—12,500-Kv-a. HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER WITH END HEAD REMOVED

can be filled with oil and drained without dismantling the machine or losing any hydrogen.

Fig. 4 shows the 20,000-kv-a. condenser located near Charleston, W. Va., at the Turner Substation of the Appalachian Electric Power Company. This machine is also placed out of doors and it has the same design as

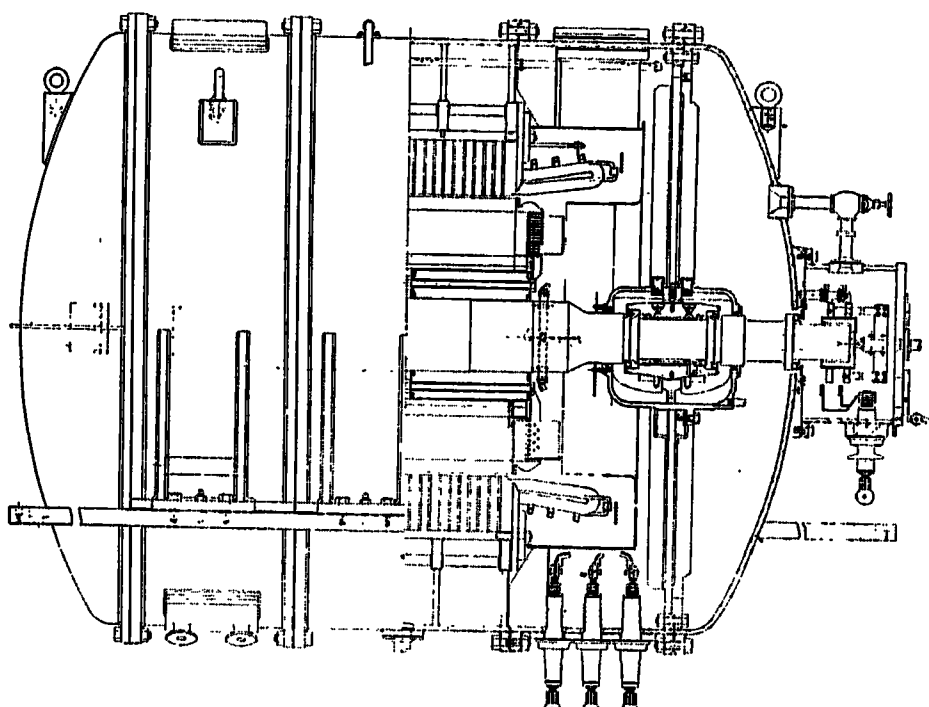


FIG. 3—SECTIONAL VIEW OF THE 12,500-Kv-a. HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER

the 12,500-kv-a. condenser except that its capacity is higher. Fig. 5 shows the 20,000-kv-a. condenser assembled on the test floor. The two ladders enable the operator to manipulate the vent valves on the top headers of the coolers and the hydrogen valves at the top of the machine. The field collector is located in the small housing which is bolted to the end head. A high-

speed induction motor-driven exciter set, located inside of the substation, furnishes the excitation.

Fig. 6 shows the weather-proof pit beneath the condenser. In this pit are located the cooling water circulating pump, the oil pump for filling the bearings and furnishing high pressure oil for starting, the hydrogen supply tanks, the hydrogen pressure gage, the indicating thermometers, the automatic hydrogen pressure control, the rotor fan pressure gage for indicating the hydrogen purity when the machine is in operation, the thermal cell of the hydrogen purity indicator which indicates the hydrogen purity at all times, and the various valves for controlling the water, oil, and hydrogen.

IV. EXPLOSION-PROOF FRAME

The stator frame consists of three sections and two heads bolted together as shown by Fig. 3. The main joints of the frame are gasketed gas-tight and they have practically no hydrogen leakage. The large middle

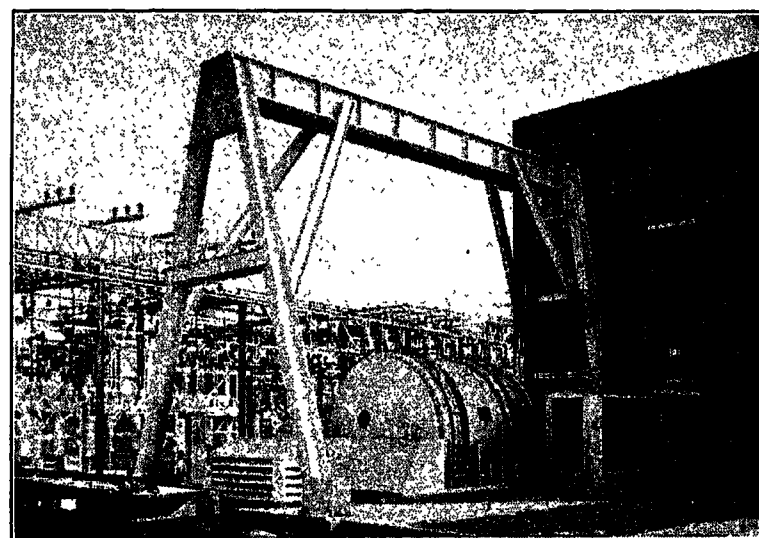


FIG. 4—THE 20,000-Kv-a., 900-REV. PER MIN., THREE-PHASE, 60-CYCLE, 11,500-VOLT OUTDOOR HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER. APPALACHIAN ELECTRIC POWER CO., CHARLESTON, W. VA.

section holds the armature punchings and windings and the two smaller sections hold the internal surface coolers and bearings. The three sections are supported on base rails with feet. All piping and connections, except the hydrogen inlet pipe and the field winding terminals, are brought out at the bottom of the frame in the pit. The frame is fabricated entirely from steel plate. The elimination of castings, which are sometimes porous, is not only in keeping with present day dynamo machine construction, but it insures minimum hydrogen leakage.

In order to minimize the effect of an explosion resulting from careless operation, these condensers were provided with a cylindrical explosion-proof frame designed to resist the disruptive force of the most explosive mixture of hydrogen and air at atmospheric pressure. The frame of the 12,500-kv-a. condenser without windings, coolers, and piping, was filled with the most explosive mixture of air and hydrogen, and the gas was ignited with a spark plug. No damage

resulted from the explosion which developed a maximum pressure of 85 lb. per sq. in. as recorded by an instantaneous pressure recorder. If the machine had been completely assembled with all of the various metallic parts, especially the coolers, the pressure would have been only about 50 lb. per sq. in. This test also showed that an explosion would have no detrimental effect on the insulation. It is very unlikely that the gas in the machine will ever reach the most explosive mixture of air and hydrogen of 5 to 2 by volume. For any other gas mixture, the explosive force would be very much reduced. The theoretical pressure of 180 lb. per sq. in.

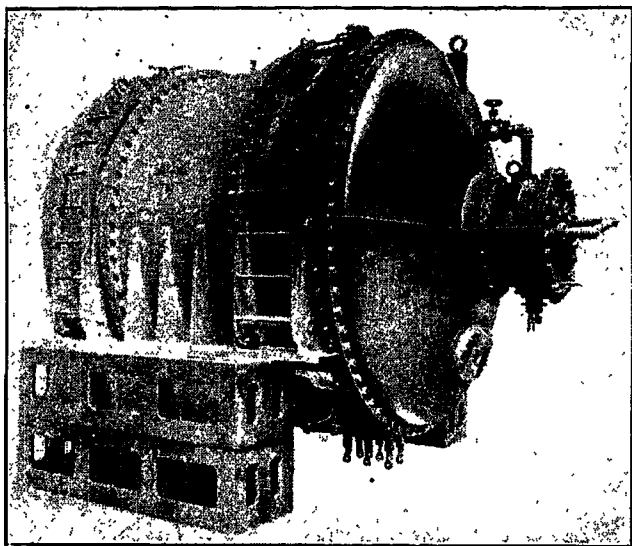


FIG. 5—20,000-KV-A. HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER ASSEMBLED ON THE TEST FLOOR

with an air-hydrogen explosion could be obtained only if no heat were absorbed by the explosion chamber and its contents.

V. ARMATURE WINDING

The armature winding consists of multi-turn coils insulated entirely with mica, bonded with black insulating varnish. The individual turns are also insulated with mica throughout their entire length. The armature coils have the standard insulation thickness for air operation, and in addition to the vacuum-filling treatment, the coils were covered with an oil resisting varnish to prevent any oil vapor, if present, from penetrating the coil insulation. The six armature leads are brought out through gas-tight terminals as shown by Fig. 3.

VI. CARBON SEAL

It was previously stated that no shaft seal was required because the shaft did not extend through the shell. However, it was thought advisable to place a seal around the shaft where it enters the collector housing in order that the collector brushes might be adjusted and renewed without losing an appreciable amount of hydrogen from the main shell. This seal obviously does not function unless the collector housing end plate is removed. The seal consists of a carbon ring which is held against a shoulder on the shaft by a bellows and six springs equally spaced around the shaft.

VII. HYDROGEN VENTILATION

Each end of the frame contains two semi-circular surface coolers as shown by Fig. 2. The cooler heads can be removed and the tubes cleaned without dismantling the machine or losing any hydrogen. The four cooler units are piped in multiple, and air vents and drain valves allow the coolers to be thoroughly drained to prevent any water in the cooler from freezing in the winter if the machine is not in use.

The rotor poles and fans force the ventilating gas through the stator ducts to the back of the stator frame. Then the gas passes through the semi-circular coolers and is returned to the rotor and recirculated. Provision is made for ventilating the collector housing by circulating hydrogen through the housing by means of two pipes as shown by Fig. 5. Two dial thermometers indicate the temperatures of the ventilating gas before and after it passes through the cooler. If the temperature of the gas leaving the cooler exceeds 40 deg. cent., the thermometer rings an alarm. Indicating thermometers also ring an alarm if the bearing temperature exceeds 70 deg. cent.

VIII. HYDROGEN LEAKAGE

An automatic pressure regulating switch and valve maintain the hydrogen in the machine always slightly above atmospheric pressure to prevent air from leaking into the shell. The hydrogen pressure in the machine varies with its internal temperature. The average pressure is around $\frac{1}{2}$ lb. per sq. in. and the leakage of the machine itself at this pressure is about 6 cu. ft. per day which costs around 10 cents. The hydrogen

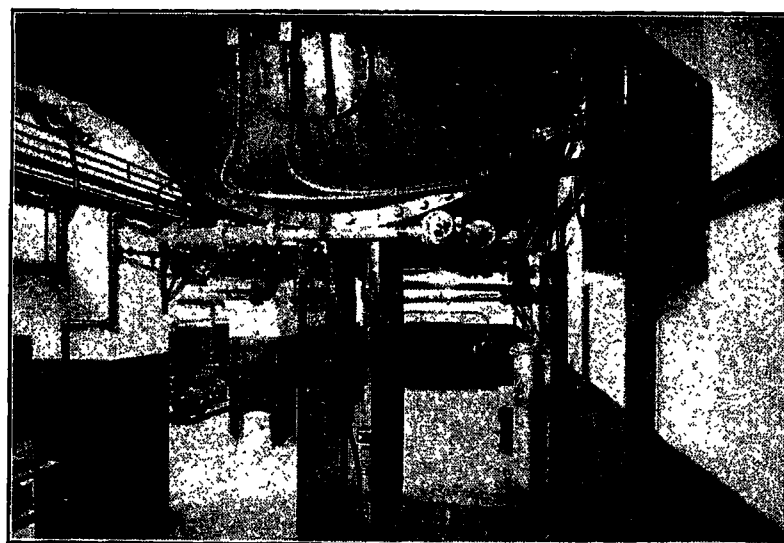


FIG. 6—WEATHER-PROOF PIT OF THE 20,000-KV-A. OUTDOOR HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER

purity indicator wastes a small amount of hydrogen for its thermal analysis. Thus, the total hydrogen cost is very small, from 15 to 20 cents per day, depending upon how much is used by the hydrogen purity indicator.

IX. INCREASED OUTPUT

The excellent cooling properties of hydrogen enable a given machine to operate at an increased output at the same temperature rise. If the hydrogen pressure is in-

creased above atmospheric pressure, the output can be further increased. Numerous heat runs were made in which the hydrogen pressure was increased in steps up to 25 lb. per sq. in. These tests indicated that a hydrogen pressure of 15 lb. per sq. in. gave the best results. If the pressure is increased above this amount, the windage loss increases appreciably and the gain in output is not so marked.

The following table shows how the output of salient pole high-speed condensers increases with the same temperature rise when hydrogen is used for the cooling medium.

Cooling medium	Machine output
Air at atmospheric pressure.....	100 per cent
Hydrogen at a pressure slightly above atmospheric pressure.....	125 per cent
Hydrogen at a pressure of 15 lb. per sq. in. above atmospheric pressure.....	140 per cent

Naturally, these figures will vary with different types of machines. The field winding is usually the limiting feature because it is more difficult to ventilate, and magnetic saturation and stability impose more limitations on the rotor than on the stator.

X. DECREASED LOSSES

The introduction of hydrogen into a machine reduces the rotor windage loss to about eight per cent of its loss in air. The following table shows the saving in windage loss of the two condensers:

Machine capacity kv-a.	Reduction of windage loss accomplished by hydrogen
20,000	85kw. (0.42 % of machinerating)
12,500	51kw. (0.41 % of machinerating)

The internal copper temperatures are less with hydrogen, and so the copper losses will be slightly reduced. Fig. 7 shows the total losses of the 20,000-kv-a., three-phase, 60-cycle, 11,500-volt hydrogen-ventilated condenser at various loads. The losses are given for air at atmospheric pressure, for hydrogen slightly above atmospheric pressure, and for hydrogen at 15 lb. per sq. in. At 20,000 kv-a. the total loss of this condenser in hydrogen is only 1.5 per cent.

XI. COST OF HYDROGEN-VENTILATED SYNCHRONOUS CONDENSERS

The initial cost of any new type of apparatus is usually high, and the development of hydrogen-cooled machines has not yet reached the point where its cost alone is the same as that of a standard air-cooled machine of the same size. The gas-tight construction, the water coolers, and the auxiliary control features naturally increase the cost which is partly offset by the increased rating obtainable. However, the value of the improved efficiency due to the lower windage loss (Fig. 7) will probably prove the deciding factor in any

cost comparison. The capitalized value of the two per cent losses of a synchronous condenser is about the same order of magnitude as the first cost of the condenser installation, so that any reduction in the losses is of the same economic value as an equal reduction in cost. Thus, when decreased losses, increased capacity, lower internal temperatures, reduced fire risk, longer insulation life, cleanliness, quietness, and saving in building expense (outdoor operation) are capitalized,

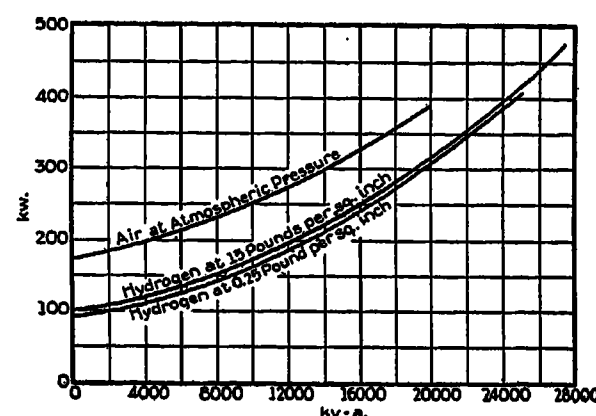


FIG. 7—TOTAL LOSSES OF THE 20,000-KV-A., 11,500-VOLT, 60-CYCLE, HYDROGEN-VENTILATED SYNCHRONOUS CONDENSER

a large hydrogen-ventilated machine has a real economic justification.

CONCLUSIONS

The results obtained on these two hydrogen-ventilated synchronous condensers to date have been very encouraging and three more machines, rated 15,000-kv-a., are under construction. Not only have the hydrogen features of the machines performed satisfactorily, but during the past winter the machines have operated successfully out of doors with no protection from the weather. Thus outdoor synchronous condensers, whether air or hydrogen cooled, should give reliable service at a reduced overhead expense.

Electrical manufacturers are constantly striving to improve the efficiency and the ventilation of rotating machinery. High grade magnetic steel, transposed armature windings, correct magnetic structure shapes and proportions, improved rotor fans and ventilating ducts, thinner and more compact insulation, etc., all tend to reduce the losses and the size of a machine. However, these refinements have been worked over so exhaustively that further improvements in performance characteristics by these means will perhaps be relatively small. Any appreciable gain must come by the way of a radical change in the machine structure, materials, or ventilating medium. Hydrogen cooling is one of these radical departures from tradition which opens new avenues of progress and rotating machines with 99 per cent efficiency may soon be a reality.

ACKNOWLEDGMENT

The cordial cooperation of the New England Power Company and the Appalachian Electric Power Company in obtaining the various tests on these hydrogen-ventilated synchronous condensers is greatly appreciated.

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Discussion

Philip Sporn: The use of hydrogen as a medium in which to operate rotating machines is, I believe, a logical development and a big step forward. The logical expansion of this development should be its application to turbo alternators. Here, of course, the problem of designing an explosion-proof frame is not as simple as in the case of the condenser, but the experience gained with the synchronous condenser may definitely indicate that such precautions and safeguards are not at all necessary.

The use of hydrogen offers the solution to another problem that without hydrogen is not so simple to solve. I refer to the use of voltages of the order of 33,000 or higher for turbo alternators—voltages which we undoubtedly must employ if the size of machines continues to grow. Where the impulse-strength problem does not have to be considered, hydrogen coupled with other developments in insulation means an almost certain assurance of continuity of service as far as the high-voltage phase of the problem is concerned.

Another development that the further expansion of the use of hydrogen will make possible is the outdoor steam generating station. The total or partial elimination of the turbine room will certainly reduce costs.

At the Turner substation of the Appalachian Electric Power Company (one of the subsidiaries of the American Gas and Electric Company) we have had a 20,000-kv-a. hydrogen condenser in very satisfactory operation for almost six months. We have had slightly more leakage of hydrogen than has been indicated by Mr. Wieseman; it has been of the order of 75 to 100 cu. ft. a week, but some of this loss is undoubtedly due to very small leaks in the piping that have not been detected.

On two additional hydrogen condensers which are being built for subsidiaries of our company, we expect to reduce this figure considerably by eliminating the bubbling of gas to the atmosphere for sampling purposes. Instead, the sampling will be taken care of by a continuous circulation of hydrogen through the thermal sampling cell, the sample gas being returned to the machine.

L. L. Perry: With mine-mouth central stations and reliable transmission lines such as Mr. Sporn's company has been operating for many years, the fuel cost is below the fixed charge on the investment when the capacity factor climbs up around 0.08. The economy curve of fuel consumption cannot be expected to drop in the future as rapidly as in the past. Hence the investment cost per kw. that averages around \$100 is now getting the attacks of executives, and the thought expressed by Mr. Sporn is a very natural one.

High-tension bus bars about twenty years ago began to go outdoors, although some 220-kv. busses in the mountain country still linger inside. Soon oil circuit-breakers and transformers followed the trend toward the out-of-doors, especially at high

voltage. Now we are putting the generator busses, instrument transformers, circuit breakers, and connections outdoors, and enclosing them all in metal. With the hydrogen-cooled generator, there is a strong incentive to do as Mr. Sporn suggests. If the hydrogen escapes to the air, rather than to the closed turbine room, the chance of a confined explosive mixture is reduced. But we must not overlook the fact that we shall have to watch for effects produced by the greater range of temperatures and be prepared to take such precautions as will insure at least as good, if not greater, reliability of service from these generator units than we get now in the enclosed turbine room.

The wider use of electricity goes hand in hand with the demand for greater reliability. We are really now more or less pulling ourselves up by our bootstraps. We go to the designing engineers and ask for a larger generator. They give us a larger generator which has probably as great reliability as in the past, if not greater, and probably reduces our cost of operation and that increases the demand for electric current. If we get the greater reliability as well as the lower cost, that means we go again and ask for still larger machines. So we are getting to the point where the designing engineer may be forced to use the hydrogen in order to meet the demands of the power companies for the larger apparatus.

C. J. Fechheimer: In the applications of hydrogen to the large turbine generator the construction shown in this paper cannot be used for the reason that it is necessary to bring a shaft through the end bells and then according to our calculations, it would seem not to be feasible to make the structure explosion-proof. The stresses in the end bells become prohibitively high in the event that an explosion should take place.

In regard to the danger of an explosion, it seems that, in golf parlance, this is a "mental hazard." We are naturally afraid of explosions, but the risk involved is almost nil if precautions are taken as suggested by Mr. Wieseman. If the generator is first scavenged with an inert gas, such as carbon dioxide or nitrogen, you can quite readily get the mixture of the inert gas and air such that when followed by the incoming hydrogen, the explosion danger will disappear entirely.

There are various ways of computing the amount of scavenging gas needed. One explosion limit is 70 per cent hydrogen and 30 per cent air. The scavenging gas is introduced so as to secure a mixture of 30 per cent air and 70 per cent inert gas, although it may not be necessary to go quite that far. Then hydrogen is introduced, the mixture of other gases being expelled simultaneously. There is then no danger, even though some means of ignition be present. The amount of scavenging gas needed can be computed on the assumption that there is perfect diffusion, which is a conservative basis for computation. In that case it can be shown that the following formula applies:

$$\frac{\text{Volume of gas put into machine}}{\text{Space in generator which is occupied by gas}} = 2.3 \log_{10} \frac{\text{Per cent of machine volume that is air initially}}{\text{Per cent of machine volume that is air finally}}$$

In this case, the right-hand side becomes: $2.3 \log_{10} \frac{100}{30} = 1.2$.

That is, only 1.2 × machine volume of inert gas need be introduced to secure safety against explosion.

When going the other way, that is, when changing from hydrogen to air, the same ratio does not hold. The same method of computation may be used, substituting the word "hydrogen" for air. For safety, the hydrogen content should be reduced to about 10 per cent, with 90 per cent inert gas. If there were 100 per cent hydrogen initially, about 2.3 volumes of inert gas would be required.

In regard to the explosion limit, I might point out one or two other comparisons. Practically every householder in the United

States uses gas in the home, for heating, or cooking, and we seldom hear of an explosion, but the potential risk there is greater than it is in a hydrogen-cooled machine with the precautions that are taken for safety.

Also in oil circuit breakers, there are far greater risks from the explosion standpoint than in a hydrogen-cooled machine. My own opinion is that in a few years we will get over the scare and our synchronous condensers will not have to be made explosion-proof.

In the design of the synchronous condenser or any other machine in which hydrogen cooling is to be used, it becomes increasingly important to know about how much volume of gas will be circulated in the machine and what the velocities and pressures are, in order intelligently to design the coolers, the fans, and other parts. Therefore, a systematic study of ventilation of this type of machine is of great importance. At the Westinghouse Company, this study has been going on for a number of years and is about completed at the present time. It is interesting to note in this connection that the volume of gas per unit of time calculated is substantially the same with hydrogen as it is with air; that is, if the only change is that of substituting hydrogen for air. The pressure of the gas naturally falls in proportion to the density.

Mention is made in the paper that the fans on the machine were used for measurement of the percentage of hydrogen, the pressure drop across the fan being a measure of the density of the gas and from the density of the gas the percentage of hydrogen can be determined. In our own work we have found an external fan to be more convenient, particularly as this device can be used when the main unit is shut down, whereas by the method suggested by Mr. Wieseman, the scheme is inoperative when the synchronous condenser is not running. Use is made of a very small fan driven by a substantially constant-speed motor.

In the design of machines of this type, it is of value to investigate whether the flow of the gas in the vent ducts is laminar or turbulent. Laminar flow pertains to flow in layers, and turbulent flow pertains to whirls or eddies. With turbulent flow, the heat is transferred from the surface to the gas better than with laminar flow. The change from laminar to turbulent flow is dependent upon the velocity, density, and viscosity of the gas. It is quite possible that in parts of some of the vent ducts the flow may change from the turbulent to the laminar state, when changing from air to hydrogen, and the designers should be guided accordingly so that high local temperatures will not be reached. Investigations along this line have been conducted recently, by G. W. Penney, but we are not yet ready to report upon them.

The use of structural steel in this application is important. If the signal advance in the last few years in changing from castings to structural steel had not been made, it is possible that these machines could not be operated with the very small leakage as we do today. It is largely because we are able to weld steel and make the joints very tight that the very small leakage as reported by Mr. Wieseman has been obtainable.

In regard to the cost, according to the calculations which we have made, it would seem that in the large machines, the costs will not be as great as Mr. Wieseman has found. Costs can not be based upon one or two machines, because the first machines are always far more expensive than those which are made later. It is difficult at present to say what these costs will be, but for the same rating, not for the same machine, (with smaller machines for hydrogen than for air), it would appear that the cost would be less for the hydrogen than for the air-cooled machine.

L. A. Doggett: The paper states, "A mixture of hydrogen and air will not explode if the hydrogen content, by volume, is more than 70 per cent or less than 10 per cent."

Now there is no question that the manufacturer can maintain

better than 70 per cent inside the apparatus. Equal care should be used to keep the percentage outside less than 10 per cent. On Jan. 15, 1926, there occurred inside the submarine E-2 at the Brooklyn Navy Yard, a disastrous explosion, due to hydrogen escaping from the Edison battery. Subsequently the submarines were equipped with hydrogen detectors which sounded an alarm at 2 per cent of hydrogen.

Therefore every precaution should be taken to see that 10 per cent mixtures cannot occur in any confined space in the neighborhood of the apparatus. The only possibility of this occurring is when the apparatus is indoors or when there are poorly ventilated inverted pockets near the apparatus when outdoors.

B. A. Behrend: I should like to review the problem of hydrogen cooling from a little different and perhaps a little broader angle. I believe that it will be essential within the immediate future to use almost exclusively out-of-door installations. Our transformers, switches, and generating units will be placed outdoors. If such apparatus is placed out-of-doors, the methods of ventilation will naturally undergo careful scrutiny. For the last forty years we have designed electric generating units with air cooling. We are now beginning to scan the medium of cooling these units. Mr. Wieseman and Mr. Fechheimer have told us that they have obtained good results with hydrogen. But there are, of course, other means of cooling.

In Europe oil-cooling of stators has been discussed. Oil as a cooling medium should be scrutinized before hydrogen cooling is too generally adopted as the best solution for cooling large generating units.

With the development of non-corrosive metals, especially copper-nickel alloys like Monel metal, we are in a much better position to make safe out-of-door electric generating units or synchronous condensers, because we may expose the metal continually to the weather without danger of corrosion.

As regards the size of the individual units, I predicted in 1907 that we should have to go to 25,000 kw.

We then predicted larger units than 25,000 kw., setting the limit at approximately 100,000. A year and a half ago, I stated in New York that I believed the final limit would be about 200,000 or 250,000 kw.

It is interesting to put on record here that I believe the limit of individual generator capacity will be approximately 250,000 kw. and that even the power companies will not ask us for greater capacities.

F. D. Newbury: I am sorry so much has been said about explosions. I think it has already been over-emphasized. Mr. Wieseman has pointed out that the 15,000-kv-a. condenser has less than 2 per cent of the possibility of danger of the 2000 hp. steam boiler. Yet he has made the condenser explosion-proof. I believe Mr. Wieseman will agree that this is a concession to our fears and not in accordance with the facts of the situation.

When we come to the real problem, the application of hydrogen cooling in turbine generators, it will be exceedingly difficult, if not impossible, to make the casing heads sufficiently strong with the necessary hole in the center for the shaft. So I feel that it is unfortunate that these first machines have been made explosion-proof when we cannot conveniently continue the practice, and when, as I believe, the practice is not justified by the conditions.

The second point I would make is that the outdoor installation is not necessarily tied up with the hydrogen cooling; closed-circuit air cooling is equally applicable. It is also unnecessary to consider that a hydrogen-cooled machine must be placed out-of-doors. In our experimental work in East Pittsburgh, we had a 7500-kv-a. turbine generator in a special test room just about large enough to contain the apparatus. Due to faulty seals there was a leakage of about 40 cu. ft. per hr., instead of that amount per week, and in spite of the comparatively small room

there was no dangerous contamination of the air. So certainly with any commercial leakage factors and with reasonable room size, leakage is no reason for putting a hydrogen-cooled machine out-of-doors.

C. M. Gilt: I am very glad to see the commercial development of hydrogen cooling and we hope to see it applied shortly to turbo alternators where the advantage would appear to be greatest.

Between two and three years ago, the Brooklyn Edison Company gave serious consideration to hydrogen cooling for a 35,000-kv-a. frequency changer which we expected to install. We did not believe it worth the cost to make the housings explosion-proof and our designs were for an outdoor installation in order to keep the cost at a minimum.

Even though the unit would be rated 35,000 kv-a., with a relatively high peripheral speed for a frequency changer, the gain made by reducing the size would not offset the increased cost of the enclosure and the reduction in losses would not equal the extra carrying charges of the hydrogen-cooled machine as compared with an air-cooled machine installed in a building.

I have a suspicion that if all the cumulative advantages of hydrogen cooling, such as thinner insulation and the consequent over-all reduction in size, were adopted, even the relatively low-speed frequency changer might show economic advantages. Naturally, the conservatism of operators and manufacturers restrains one from going all the way in the reduction of size which may be found possible with the hydrogen cooling, but I expect that we will see marked economies in the design following the early experience in operation of hydrogen-cooled apparatus.

H. W. Brown: I should like to ask Mr. Wieseman whether he has taken into account the advantage in design, resulting in longer life of a machine that is not in an atmosphere containing oxygen. Generally there is deterioration of the insulation by oxidation. This does not apply to conductors that are not exposed to the air, but in other conductors there is a deterioration which is greater at high than at low temperatures. It would seem, then, that where the windings are in an atmosphere of hydrogen we could either have a longer life of a machine with the same rating, or the same life with a higher rating.

I. A. Terry: Mr. Gilt refers to the application of hydrogen-ventilation to frequency converters. There are two problems in connection with such an installation which require careful consideration. One relates to stability; the other is a mechanical problem.

In the introduction of his paper Mr. Wieseman pointed out that the advantages in ventilating a machine with hydrogen result in an increased output of 25 per cent or more, depending upon various factors, one of which is the stability required. Assuming that lagging kv-a. is not important, this would mean that a 10,000-kv-a. air-cooled condenser could be rated 12,500 kv-a. when hydrogen-ventilated by increasing the field and armature current. It is not possible to increase arbitrarily the rating of a synchronous generator, if the same degree of stability is to be maintained, by simply increasing the armature current and field current. It has been shown* that the short-circuit ratio is a measure of the stability of a generator under any given set of operating conditions. And since the short-circuit ratio is inversely proportional to the stator current and directly proportional to the no-load field current, an arbitrary increase in the armature current must be accompanied by a proportional increase in the no-load field current if the hydrogen-ventilated generator is to have the same degree of stability as the present air-cooled machines. Similar remarks apply to the motor of a frequency converter, the stability being determined by the pull-out load, instead of the short-circuit ratio.

The mechanical problem arises in making the frequency converter gas-tight. Mr. Wieseman pointed out that hydrogen

cooling can be easily applied to a synchronous condenser, because the entire machine, including bearings and shaft, can be enclosed in a gas-tight shell as contrasted with the application to a turbine generator where a shaft seal is required. In a frequency converter either shaft seals must be provided or the whole set enclosed in a large gas-tight shell. Both types of construction have certain advantages and disadvantages. In addition for parallel operation of frequency converters, if the operator is to have control of the load division, it is necessary to have one stator frame of the set arranged for rotating. This again complicates the construction of a gas-tight shell.

R. W. Wieseman: Mr. Sporn stated that operating experience indicated a hydrogen leakage of 75 to 100 cu. ft. per week and that this was a little larger leakage than I mentioned in the paper. The paper gives the total cost of the hydrogen leakage as 15 to 20 cents per day, and this is just about the cost of 75 to 100 cu. ft. of hydrogen leakage per week as given by Mr. Sporn.

I quite agree with Mr. Fechheimer that the explosion risk of a hydrogen-cooled machine is almost nil if the machine is given ordinary supervision. The explosion problem is always associated with any new development which utilizes an explosive material. This was anticipated when the first machine was built, and therefore the explosion-proof shell was used to make sure that no difficulty would be experienced.

In regard to the amount of scavenging gas required, I think it desirable to displace practically all of the air with carbon dioxide and then displace the carbon dioxide with hydrogen. If the machine is filled quickly little diffusion will take place and the volume of the inert gas used should be about the same as the gas volume of the machine. It is important that all of the carbon dioxide be expelled from the machine in order to obtain minimum windage loss, and for this reason it is desirable to scavenge with hydrogen quite thoroughly. It is a simple operation to fill a machine with hydrogen. In fact it is not even necessary to use a hydrogen purity indicator for this operation, if an inert gas such as carbon dioxide or nitrogen is used to displace the air in the machine before the hydrogen is admitted.

The external hydrogen-fan purity indicator mentioned by Mr. Fechheimer is a very good scheme. It operates under the same principle as the internal-fan method described in the paper. We use the internal-fan purity indicator only as a check on the thermoelectric hydrogen purity indicator which gives the purity of the gas whether the machine is in operation or shut down. The thermoelectric purity indicator is a direct-reading instrument and it does not require a driving motor.

Mr. Fechheimer points out that the cost of hydrogen-cooled generators should be less than we obtained on synchronous condensers. That naturally depends upon the capacity of the generator. Up to the present time, generators have been built which have about three times the capacity of the largest synchronous condenser. Naturally, the hydrogen features of these large generators should cost less than those of a condenser. Furthermore, the saving in windage loss is much more in the case of a large high-speed turbine generator. There are many factors which enter into the cost of a new type of machine and these factors are further modified by the location and the conditions at the substation or power plant. Consequently, at this stage of the development, it is rather difficult to give a ratio of the cost of a hydrogen-cooled machine to the cost of an air-cooled machine.

Mr. Doggett has called attention to the explosion possibilities and points out that a minor explosion may even take place around the outside of an outdoor hydrogen-cooled machine. It should be remembered that hydrogen gas has only 1/14 the density of air and so it is practically impossible to have an explosion around the outside of an outdoor machine because, if some of the hydrogen should escape, it would immediately rise and disappear. "Inverted pockets" around the outside of a machine are not to

**Stability Characteristics of Alternators*, by O. E. Shirley, A. I. E. E. TRANS., 1926, Vol. 45, p. 1108.

be found. As a matter of fact hydrogen machines have been both inside and outside for a considerable time and no difficulty whatever has been encountered with explosions of any kind. I, therefore, do not agree with Mr. Doggett's idea of hydrogen explosions; in fact I think the explosion possibilities of a hydrogen-cooled machine have been very much overstressed.

In replying to Mr. Gilt's discussion, Mr. Terry cited two reasons why there is not so much to be gained in the use of hydrogen cooling for frequency-converter sets. Perhaps Mr. Terry has given the impression that the stability characteristic of a frequency-converter set will prevent hydrogen from increasing the rating of the set. A frequency converter, like any other dynamo machine, must be properly designed for hydrogen cooling, and although the increased rating will not be so high as in the case of a synchronous condenser, there is, however, a decided increase in the rating of the set which can be obtained with

hydrogen. The real problem in applying hydrogen cooling to a frequency converter is not so much a stability problem as a mechanical problem; namely, keeping the armature frame gas-tight and also moveable for voltage phase shifting.

Mr. Brown asked an important question, namely, how much the life of the insulation would be increased by hydrogen. As explained in the paper, tests have shown that in an atmosphere of hydrogen, corona damage is eliminated and no oxidation can take place. Just how much the insulation life will be increased by these factors is a matter of opinion at the present time because there is not much information on the subject available. The increase in the life of a varnish-fabric insulation would certainly be much more than that of mica insulation. If the hydrogen-cooled machine is not overloaded or abused, its insulation should have about twice the life of the insulation of an air-cooled machine.

Short-Circuit Torque in Synchronous Machines without Damper Windings

BY G. W. PENNEY*

Associate, A. I. E. E.

Synopsis.—The torque produced by a short circuit is first discussed in a general way, showing that it is pulsating in nature. The average value of torque is determined by the resistance and other energy losses but the instantaneous value rises far above the average value. The major part of this pulsating torque is produced by the change in stored magnetic energy. General equations are derived for the torque in a machine having negligible resistance and constant self-inductance of each winding which is referred to as an "Ideal Machine."

These equations are useful in comparing single-phase and various polyphase short circuits and for determining general tendencies. However, the numerical value of the torque is usually of most interest in salient-pole machines and here the self inductance of the armature windings is not constant. The calculation of torque from the actual inductance of the windings of a salient-pole machine is a very complicated problem. A relatively simple step by step calculation,

called the "semi-graphical method," is developed for calculating the torque from the actual currents as given by an oscillogram. The effect of resistance can be included in this calculation. The method holds for any variation in self inductance with rotor position provided that saturation is not a large factor in determining the change in stored magnetic energy, which seems to be true in cases thus far investigated.

Short-circuit torque can be measured by an instrument described in a previous paper.⁴ The torque as measured is compared with the torque as calculated by various methods. This shows that calculations based on constant self-inductance of each winding may be seriously in error, particularly if equations derived on this basis are applied to the actual currents of salient-pole machines. The "semi-graphical" method agrees reasonably well with measured values for cases thus far tested.

CONFLICTING opinions are often expressed concerning the torque produced by a short circuit. One idea frequently expressed is that since the resistance of the circuit is small compared to the reactance, the current flowing has practically zero power factor and therefore the resultant torque produced should be very slight. However, the fact that the power factor is nearly zero indicates only that the average torque during one complete cycle is small. It gives no information concerning what takes place during parts of a cycle. In designing a machine to withstand the worst possible operating conditions, the maximum value of torque which may act at any instant must be known so that the pulsating or instantaneous value of short-circuit torque must be considered. Furthermore, because of inertia reactions the same torque will not act on all parts of a machine so that to determine the force acting on any given part, the curve of torque against time must be known.

The failures occasionally produced by short circuits show that tremendous forces must result from short circuits and other transient phenomena. For example, one of the early large vertical waterwheel generators of low reactance at Niagara Falls sheared off the holding down bolts and the stator turned through a considerable angle on its foundation. In another case a frequency changer set stretched the holding down bolts and cracked the frame supporting feet when the set was connected to the line out of phase. It is only necessary to stand beside a low reactance machine when it is short circuited to realize that very severe forces are acting on the machine. Synchronizing out of phase

may produce forces which are even more severe. This paper is confined to the subject of short-circuit torque although the methods proposed can be used, with some modifications, for determining the torque during synchronizing and other transient conditions.

One difficulty in understanding the torque produced by a short circuit is the fact that the assumptions generally used for calculating the torque during normal operations do not represent the conditions during a short circuit. In calculating the torque during normal operation, it is usually assumed that the stored energy is constant so that the mechanical torque of a generator is equal to the electrical output plus the losses. If a generator is short-circuited at its terminals, its electrical output is zero and the energy losses within the machine account for only part of the torque which is known to be produced. An investigation of the stored magnetic energy of a machine during short circuit shows that this energy fluctuates very rapidly and that there is a corresponding fluctuation of the kinetic energy of the rotating mass. The transfer of kinetic energy to magnetic energy, and vice versa, must be accompanied by a torque which alternates between positive and negative values.

THE RELATION BETWEEN TORQUE AND STORED ENERGY

In order to simplify the discussion a synchronous condenser short-circuited at its terminals will be considered first. Since the terminals are short-circuited, no electrical power can flow between the machine and the line, and since there is no mechanical connection to any other machine, no power can flow to or from the synchronous condenser except that dissipated as heat.

Since there can be no transfer of energy between the machine and any outside source, the total stored energy of the machine plus the energy dissipated must remain constant. Or, expressed mathematically,

*Research Dept. Westinghouse Elec. & Mfg Co., East Pittsburgh, Pa.

4. For numbered references see Bibliography.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

$$-T \omega dt + U + \int R i^2 dt = \text{Initial stored.} \\ \text{Energy} = \text{Const.} = U_0 \quad (1)$$

Where

T = Torque at any time t (a torque which tends to accelerate the rotor is assumed negative).

U = Stored magnetic energy at time t .

ω = Angular velocity.

R = Resistance.

i = Current.

U_0 = Initial stored magnetic energy at $t = 0$.

Differentiating

$$T \omega = \frac{dU}{dt} + R i^2 \quad (2)$$

If the resistance is negligible

$$T \omega = \frac{dU}{dt} \quad (3)$$

That is to say that the torque multiplied by the angular velocity is equal to the rate of change of stored magnetic energy provided that the energy losses are negligible.

The above equations were derived for a short-circuited synchronous condenser where no energy could flow into or from the machine except in form of heat. However, the equations derived hold for any short-circuited machine. In the general case, electrical power cannot flow to or from the machine short-circuited, but mechanical power may be transmitted to or from the mechanically connected machine. Applying the law of conservation of energy to this general case, any increase in the sum of the stored magnetic energy, plus the integral of the energy dissipated, must be accompanied by a transfer of mechanical energy to magnetic energy. Conversely, any decrease in the sum of the stored magnetic energy, plus the integral of the energy dissipated, must be accompanied by a transfer of magnetic to mechanical energy.

Then,

$$U + R i^2 dt = U_0 + \int T \omega dt$$

Differentiating

$$\frac{dU}{dt} + R i^2 = T \omega$$

This is the same Equation (2) and if the resistance is negligible is the same as Equation (3). From this it is evident that if the stored magnetic energy can be determined for each increment of time, the corresponding mechanical torque can be calculated.

The torque discussed here is the resultant tangential reaction of the windings. The torque acting on individual parts will depend on the mechanical arrangement. In the case of the synchronous condenser, the shaft does not transmit any torque. In this instance the torque produced by the winding merely results in a change in speed of the rotor. The other extreme exists in a rigid rotor connected to an infinitely large flywheel

by a perfectly rigid shaft. In this case the speed of the rotor must be constant and therefore all of the torque produced must be transmitted by the shaft. Actual cases will usually be somewhere between these two extremes. The torque acting on individual parts of the machine is outside the scope of this discussion. In this discussion the term "short-circuit torque" will be taken to mean the resultant reaction of the windings.

The main purpose in studying this torque is to permit a more rational design of the mechanical parts of the machine. In designing these parts to withstand short-circuit forces the inertia reactions and deflections play an important part in determining the stresses. This requires that the duration of the forces as well as their maximum value be known, so that a curve between torque and time must be obtained. A machine must be

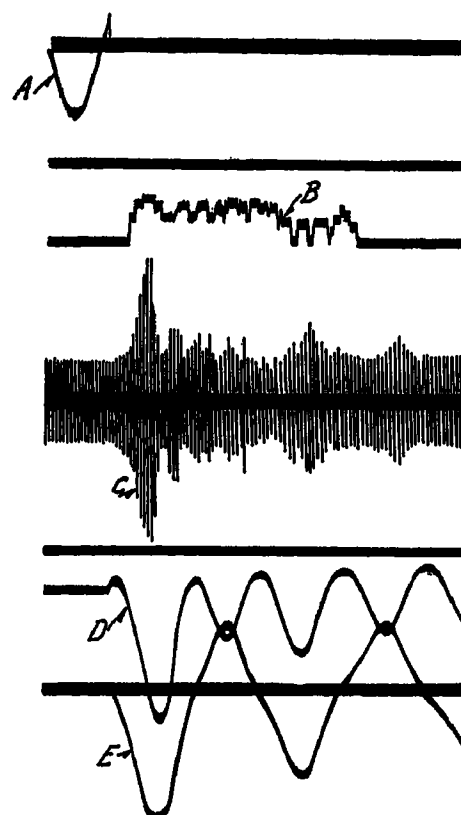


FIG. 1—TRACING OF AN OSCILLOGRAM FOR A SINGLE-PHASE SHORT CIRCUIT

- A—Terminal voltage
- B—Current through a group of contacts—the record of the contact and flywheel accelerometer measuring torque
- C—800-cycle current—the magnetic record of acceleration or torque
- D—Field current
- E—Current in the short-circuited phase

designed to withstand the worst operating conditions. A single-phase short circuit occurring at the instant when the generated voltage in that phase is zero gives a much greater torque than any other short circuit thus far investigated. Since a machine must be designed to withstand the worst conditions, this case is discussed in detail and other cases only to the extent of showing that they are smaller in magnitude.

STORED MAGNETIC ENERGY OF A ROTATING MACHINE

During open-circuit operation of a machine there is a certain field current and flux giving a substantially constant stored magnetic energy. An unbalanced load current may give some pulsation in the stored energy, but usually this is of negligible magnitude. However, at the instant of short circuit a large armature current is

produced and the field current rises to several times its normal value, which results in a corresponding increase in the stored magnetic energy.

If hysteresis and eddy currents are neglected, the flux and stored energy will depend only on the currents and rotor position and will be the same regardless of the manner in which those currents were established. In a short circuit, an increase in the stored magnetic energy is supplied by the mechanical energy of the rotor. However, to evaluate the magnitude of the stored energy for any given currents and rotor position, the rotor can be assumed to be locked in that position, and the energy required to establish the given currents and fluxes from an electrical source calculated.

SHORT-CIRCUIT TORQUE IN AN "IDEAL MACHINE"

The following conditions have frequently been assumed in discussing short-circuit currents,

1. The self inductance of the field circuit is constant.
2. The self inductance of the armature winding is constant.
3. The mutual inductance between the field and armature circuits varies as the cosine of the angle between the two windings, i. e.,

$$*M_{af} = M_{AF} \cos \alpha$$

4. The resistance of the windings is negligible.
5. An alternator to which these assumptions apply will be called an "ideal machine."

From Equation (3) $\omega T = \frac{dU}{dt}$

Since $\omega dt = d\alpha$, this can also be written $T = \frac{dU}{d\alpha}$ (4)

In the semi-graphical solution given later the actual stored energy of the rotor is computed and plotted against the angular position of the rotor. The derivative or slope of this curve is then proportional to the torque. In the mathematical solution, it is possible to compute the actual stored energy and differentiate the result to obtain the resulting torque; but this method is very complicated. The solution is simplified very much by using a method commonly employed for calculating magnetic forces. This method depends on the fact that the forces acting at any position of the rotor depend only on the currents and fluxes acting at that instant. Then to find the forces acting, the current is assumed constant and the rate of change of stored energy found for a virtual displacement of the rotor. With this assumption the current would be constant and the flux varying; in the actual case, the flux is constant and current varies.

The stored energy in a system of inductively coupled circuits is discussed by Karapetoff in *Mechanical Forces between Electric Circuits*.² It is shown that by multiplying the ampere-turns in each circuit by the flux interlinking that circuit and adding the products

for all of the circuits involved, the stored energy of the system is obtained. Or, expressed mathematically,

$$U = \sum_{u=1}^n \frac{N_u \phi_u i_u}{2} \quad (35)$$

Where N_u = Number of turns in circuit u
 ϕ_u = Flux interlinkages of circuit u
 i_u = Current in circuit u

Or expressing the flux in terms of the currents and inductances:

$$U = \sum_{u=1}^n \frac{i_u^2}{2} \sum_{v=1}^n M_{vu} i_v$$

Where M_{uv} denotes the mutual inductance between the circuits indicated by the subscripts. In case both subscripts refer to the same circuit, that is, when $v = u$ giving M_{uu} , it is interpreted to mean the self inductance of circuit u . Then this expression can be differentiated with respect to α to get the rate of change of energy for a virtual displacement of the rotor. This is given in Appendix II. It is shown that for a single-phase short

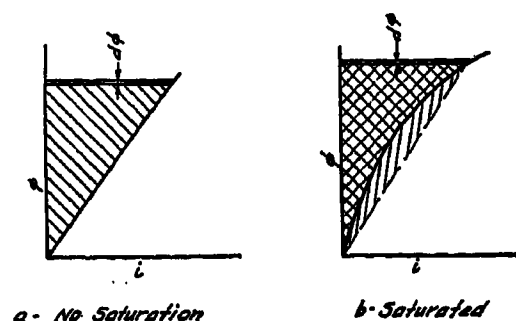


FIG. 2—FLUX CURRENT CURVES ILLUSTRATING THE STORED ENERGY IN A MAGNETIC CIRCUIT

A. Magnetic circuit with no saturation. The stored energy is shown by the cross-hatched area

B. Saturated magnetic circuit. The double cross-hatched area represents the actual stored energy. The single cross-hatched area represents the error when the energy is calculated from Equation (35).

circuit where the field and armature windings have a mutual inductance varying with the position of the rotor but constant self inductances, the variation in stored energy is given by,

$$T = \frac{dU}{d\alpha} = i_f i_a \frac{dM_{af}}{d\alpha} \quad (6)$$

Since saturation is neglected the variation in mutual inductance can be determined from the voltage generated before the short circuit. Substituting the value thus obtained in Equation (6) gives

$$\omega T = \frac{dU}{dt} = [i_a e_m \sin \alpha] \frac{i_f}{I_f} \quad (11)$$

Or, expressed in words, the torque multiplied by the angular velocity which is the instantaneous power is equal to the product of the instantaneous value of the armature current by the voltage that would have been generated under open-circuit conditions and this multiplied by the ratio of the instantaneous field current to the field current value before the short circuit. Since the field current increases to several times its

*For symbols, see Appendix I.

initial value, it is evident that this equation may give a very high value of torque. During the short circuit, the field ampere-turns are roughly proportional to the armature ampere-turns. Therefore, if the short-circuit current is increased by decreasing the reactance of the machine, it is evident that the torque will be increased approximately in proportion to the square of the arma-

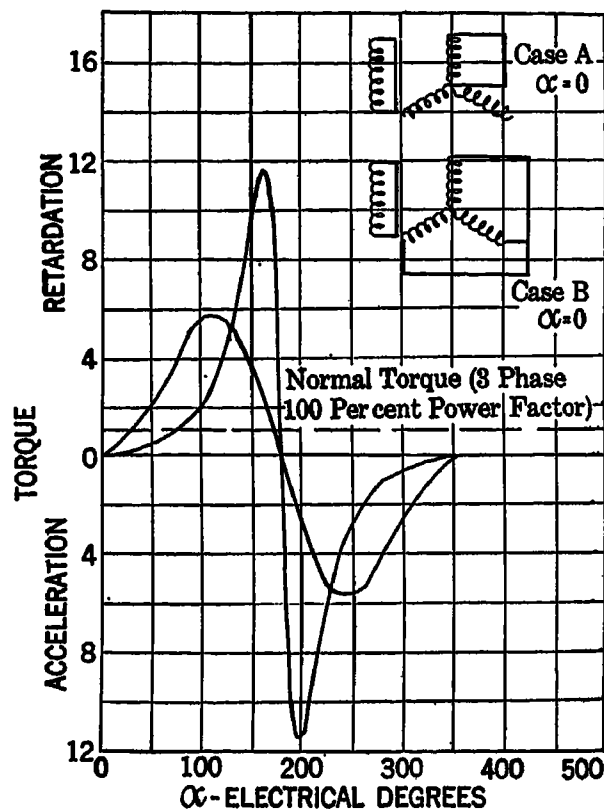


FIG. 3—TORQUE DEVELOPED BY SHORT CIRCUIT OF AN "IDEAL MACHINE"

- A. Single-phase short circuit, terminal to neutral
- B. Three-phase short circuit, terminal to terminal

Assumptions:

1. Short circuit occurs when generated voltage on phase is zero
2. Star-connected winding

$$K = 0.85 = \frac{M_{AF}}{L_f}$$

4. Peak non-symmetrical terminal-to-terminal short-circuit current equals 12 times rated r. m. s. value of current per phase

ture current, showing that in a low reactance machine the torque will be very severe.

The equation for the torque produced by a three-phase short circuit can be derived in a similar manner and gives

$$T = \frac{dU}{d\alpha} = [i_a e_a + i_b e_b + i_c e_c] \frac{i_f}{I_f \cdot \omega} \quad (14)$$

This equation is similar to Equation (11) as given, but in the three-phase short circuit the signs of the various terms must be considered. The separate circuits do not act together, which gives a slower rate of change of stored energy at any given instant and therefore a lower torque. In Appendix III, the torque is computed for a particular star-connected winding, first for a single-phase terminal-to-neutral short circuit and then for a three-phase terminal to terminal short circuit. The results are plotted in Fig. 3. The maximum stored energy is not essentially different for the two cases. In the single-phase short circuit there is a very sudden change in the stored energy from $\alpha = 125$ to $\alpha = 180$

giving a corresponding high torque. In the three-phase short circuit the variation in stored energy is sinusoidal, giving a much lower maximum value of torque.

Similar equations can be derived for other polyphase short circuits but in all of the cases thus far investigated the different circuits will not act together so that the resultant rate of change of stored energy is slower than for a single-phase short circuit. This conclusion has been confirmed experimentally for the case of a three-phase terminal to terminal short circuit and for the case of two terminals of a star-connected winding short-circuited to the neutral.* In both cases the short-circuit torque was far below that for the corresponding single-phase short circuit.

SEMI-GRAPHICAL DETERMINATION OF TORQUE

The assumptions used in the analytical solution just given are those ordinarily used in the calculation of short-circuit currents. The assumption of a constant

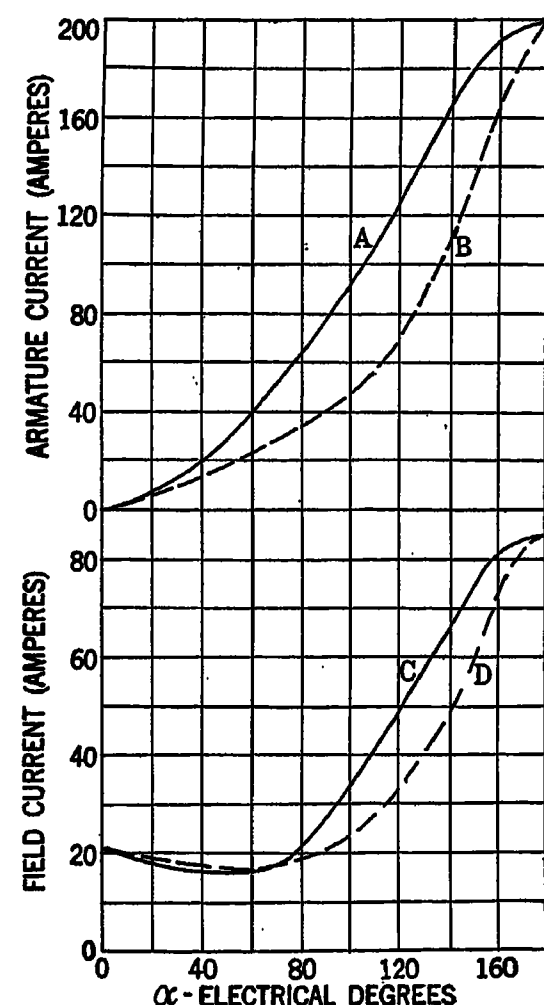


FIG. 4—COMPARISON OF ACTUAL AND THEORETICAL CURRENT WAVE SHAPE FOR SINGLE-PHASE UNSYMMETRICAL SHORT CIRCUIT
A and C,—Armature and field current, respectively, from oscillogram
B and D,—Armature and field current, respectively, from Equations (40) and (41) in paper by R. F. Franklin (B-3) with the value of K chosen to give same maximum values as A and C

self inductance of each phase represents the condition with a cylindrical rotor quite accurately but in a salient pole machine the self inductance of each phase varies with the rotor position. In the calculation of short-circuit currents we are usually mainly interested in maximum values, and the maximum value of current is

*Case (7) in the paper on *Short Circuits in Synchronous Alternators*, by R. F. Franklin.³

not seriously altered by the variation in the self inductance of the phase winding. On the other hand, the torque produced depends on the rate of change of current or rate of change of inductance so that the torque is seriously changed by the variation in the self inductance of each phase.

The equations just derived are useful for comparing a single-phase short circuit with various polyphase short circuits and determining general tendencies. A

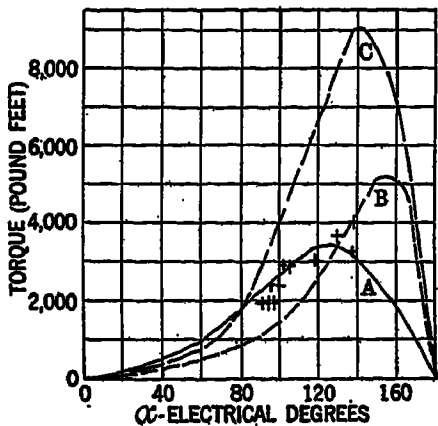


FIG. 5—COMPARISON OF METHODS OF CALCULATING TORQUE

A. Torque calculated from the "Semi-Graphical" method for current values A and C in Fig. 4. Points indicated by "+" show the torque as recorded by the contact accelerometer

B. Torque calculated for current values B and D in Fig. 4. Note that semi-graphical method and Equation (11) give the same results in this case since the current is based on constant self-inductance of each circuit

C. Result of applying Equation (11), which was based on constant self-inductance, to the actual current (Curves A and C in Fig. 4) from a machine having variable self-inductance

turbo alternator approximates the constant self inductance of each phase on which the equations were based. However, the salient-pole machine has an inherently less rugged construction than the turbo alternator, so that the determination of short-circuit torque is of greater importance in the salient pole machine where the variation in self inductance must be considered. If the variation in the inductance of the windings is accurately known and the currents calculated Equation (12) can be used to calculate the torque.

In this case the calculations become complicated so that the method is cumbersome.

The semi-graphical method has been developed for calculating the torque from an oscillogram of currents, and eliminates the necessity of determining the inductance of the separate circuits. The method is based on the assumption that the stored energy of

n circuits is equal to $\sum_{1}^n \frac{N_u \phi_u i_u}{2}$ as given by Equa-

tion (35). This equation holds for any self inductance and mutual inductance between the circuits involved, provided saturation is negligible. The flux can be determined from the initial conditions and assuming that the resistance is negligible, will remain constant during the first instant of short circuit. Then by taking the values of current from an oscillogram the energy of the magnetic field can be calculated without determining the inductance of the various circuits involved. The energy can be calculated for successive positions of the rotor and by taking the difference in successive values, the change of energy and the resulting torque can be calculated.

Since the result depends on differences between successive values, the values of current must be accurately determined and the increments of time used must be large enough so that the change in current can be measured accurately. This calculation is illustrated in Appendix IV. Successive values for one case are tabulated in Table I, and the result plotted for Curve C of Fig. 6.

Effect of Saturation. Equation (35) is based on the assumption of no saturation. In a machine some parts of the circuit are usually highly saturated. However, during the first instant of short circuit the resultant flux interlinkages of each circuit remain substantially constant. For this reason the effect of saturation upon

TABLE I
CALCULATION OF TORQUE NEGLECTING RESISTANCE

α degrees	i_f amperes	$N_f i_f \phi_f$ $2 \cdot 10^8$	i_a amperes	$N_a i_a \phi_a$ $2 \cdot 10^8$	(Joules) energy U	ΔU (Joules)	$\frac{\Delta U}{\Delta \alpha} \cdot 2.21 =$ torque (lb.-ft.)
20	27	506	0		506		
30	25.5	478	7	42.4	520	14	177
40	23.5	440	23	140	580	60	760
50	23	431	40	242	653	73	965
60	23.5	440	57	345	785	72	910
70	25.5	478	75	454	932	147	1860
80	29.5	552	94.5	572	1124	192	2430
90	36	675	113	685	1360	246	3120
100	45	843	134	811	1654	294	3720
110	55.5	1030	158	956	1986	332	4200
120	69	1295	185	1120	2415	429	5420
130	84	1575	214	1295	2870	455	5760
140	100	1875	244	1475	3350	480	6080
150	112.5	2110	273	1655	3765	415	5250
160	121	2270	294	1780	4050	285	3600
170	126.5	2370	295	1790	4160	110	1400
180	124	2320	277	1675	3995	-165	-2090
190	116	2170	252	1585	3755	-240	-3040
200	104	1950	224	1355	3305	-450	-5700
210	90	1690	190	1150	2840	-465	-5880

the change in stored energy is not as serious as it might appear from the values of current involved.

A magnetic field can be regarded as divided into parts and the energy computed separately for each part. For the part of the magnetic circuit through air or other medium of constant reluctance, the energy is given by Equation (35). This is represented graphically by the cross hatched area in Fig. 2A which is merely $\int i d\phi$. For the part of the circuit traversing iron the energy will still be given by $\int i d\phi$ but this integral will not be given by Equation (35). The double cross hatched area in Fig. 2B represents $\int i d\phi$ which is the actual stored energy in the saturated field. The single cross hatched area in Fig. 2B represents the error when the energy in the saturated circuit is calculated from Equation (35) (*i. e.*, neglecting saturation).^{1,3}

If a machine is working high on the saturation curve it is obvious that the initial stored energy will be con-

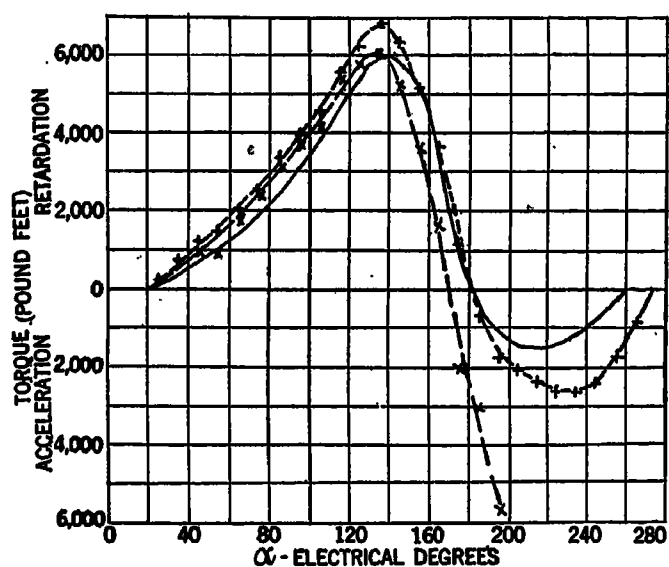


FIG. 6—TORQUE PRODUCED BY A SINGLE-PHASE SHORT CIRCUIT

B + — — — Calculated from the recorded currents considering the effect of resistance
C x — — — Calculated neglecting the effect of resistance
A — — — Torque recorded by the magnetic accelerometer
o — — — Torque recorded by flywheel and contact accelerometer

siderably in error when calculated neglecting saturation. During the short circuit the resultant flux interlinkages of any circuit remains substantially constant. The flux at some highly saturated points is reduced and the saturation at other points increased. However, in most designs the main change in the energy of the field occurs in the part of the circuit through the air and other non-magnetic material. For this reason although the initial energy may be considerably in error, the change in energy will be substantially correct when calculated neglecting saturation and therefore the torque can be calculated neglecting saturation with sufficient accuracy for this type of calculation. This conclusion is substantiated by the agreement obtained between calculations and tests as illustrated in Figs. 5 and 6.

The Effect of Resistance. Thus far the effect of resistance has been neglected. Assuming that the currents are taken from an oscillogram, the effect of resistance on the torque calculation is two-fold. First,

the resultant flux interlinkage of each circuit is constant only when the resistance of the circuit is negligible. Actually the electromotive force to overcome the resistance drop in a short-circuited winding must be supplied by the change in flux interlinkages of that

circuit (*i. e.*, $Ri = e = N \frac{d\phi}{dt}$). Secondly, the power

represented by the resistance loss is usually not negligible because of the large values of current involved.

These two effects of resistance can be incorporated in the step by step calculation of torque. The decrease in flux interlinkages can be calculated for each increment of time and this value used to obtain the actual flux interlinkages and corresponding stored energy. The torque corresponding to the resistance loss can be calculated and added to the torque resulting from the change in stored energy. This calculation considering resistance is illustrated in Table II of Appendix IV and the torque obtained plotted as Curve B of Fig. 6.

These calculations are for the short-circuit recorded on the oscillogram of Fig. 1. On this oscillogram the terminal voltage, field current, and armature current are shown. Also the torque is recorded on the oscillogram by the accelerometer described in a paper at the Pittsfield Regional Meeting in 1927.⁴ This measures the torque by two different devices. The first device gives a continuous record of the torque and is called the magnetic accelerometer. The second device merely gives points on the torque time curve and is called the flywheel and contact accelerometer. Both devices measure the torque by measuring the acceleration imparted to the rotor. The two measurements of torque are also plotted in Fig. 6. The record B of Fig. 1 is the current through the flywheel contact. As the torque increases during the first half cycle of the short circuit, each sudden change in the current through the contact represents the point where one flywheel contact opened which is a point on the torque time curve. These points are shown by the small circles in Fig. 6.

The oscillogram of Fig. 1 was taken from a 60-cycle alternator, short-circuited at 25-cycle frequency. The field and armature were both short-circuited at the same instant. This oscillogram has been used to illustrate the method of calculation because the effect of resistance is exaggerated. For the first half cycle the calculation neglecting resistance gives almost the same result as the calculation considering resistance as shown by the agreement of Curves B and C on Fig. 6. The reason for this agreement is that the two effects of resistance mentioned above tend to annul each other. The decrease in flux interlinkages diminishes the rate of increase of stored energy, thereby reducing the torque while the resistance losses increase the torque. However, during the second half cycle the two effects do not cancel each other so that neglecting resistance a very high negative torque would be obtained while when

resistance is considered the calculated torque agrees reasonably close with the measured value.

Another point of interest in connection with curves of Fig. 6 is that the initial field current used was the normal value for 80 per cent power factor, but since the machine was on open circuit before the transient this gave a point high on the saturation curve. Yet the calculations neglecting saturation are in close agreement with the tests.

DISCUSSION OF RESULTS

The torque produced by a single-phase short circuit varies greatly with the position of the rotor at the instant when the short circuit occurs. This discussion has been devoted almost entirely to the subject of short circuits occurring at the instant when the terminal

assumptions frequently used in discussing short-circuit currents would apply. The equations for currents derived on this basis are quite generally applied to salient-pole machines with reasonably satisfactory results. However, as has been mentioned, it must not be assumed that the equations for torque derived using the same approximations can be as generally applied. Figs. 4 and 5 are intended to emphasize this fact. In Fig. 4 the actual wave shape of the currents for a certain machine are compared with the wave shapes as given by the equations derived by Franklin,* assuming constants which would give the same peak value of current in both cases. This agreement is satisfactory for most purposes. However, since the torque depends on the rate of change of current the value will be very different for the two cases. Curves

TABLE II
CALCULATION OF TORQUE CONSIDERING THE EFFECT OF RESISTANCE

Note: This example exaggerates the effect of resistance since a 60-cycle machine was short circuited while running at 25-cycle frequency and since both field and armature terminals were short circuited.

α degrees	$\frac{R_f i_f \Delta t}{N_f \Delta \phi_f} =$ 10^8	$\frac{N_f \phi_f}{10^8}$	$\frac{N_f \phi_f i_f}{2 \cdot 10^8}$	$\frac{R_a i_a \Delta t}{N_a \Delta \phi_a} =$ 10^8	$\frac{N_a \phi_a}{10^8}$	$\frac{N_a \phi_a i_a}{2 \cdot 10^8}$	U (joules)	$\frac{\Delta U}{\Delta a} \cdot 2.21$ torque (lb.-ft.)	Torque from resist. losses	Total torque lb.-ft.
20	0	37.5					502			
30	0.13	37.37	475	0.02	12.08	42	517	190	45	235
40	0.13	37.24	435	0.06	12.02	138	573	710	52	762
50	0.12	32.12	425	0.10	11.92	240	665	1140	85	1225
60	0.12	37.00	432	0.14	11.88	336	768	1310	138	1448
70	0.12	36.88	468	0.19	11.69	435	903	1840	225	2065
80	0.14	36.74	540	0.24	11.45	540	1080	2240	345	2585
90	0.21	36.53	655	0.31	11.14	625	1280	2530	506	3036
100	0.26	36.27	815	0.39	10.75	715	1530	3170	768	3938
110	0.33	35.94	995	0.46	10.29	810	1805	3480	1100	4580
120	0.41	35.53	1225	0.53	9.76	896	2121	4000	1590	5590
130	0.53	35.00	1475	0.66	9.10	960	2435	3980	2260	6240
140	0.65	34.35	1721	0.75	8.35	1020	2741	3880	2950	6830
150	0.76	33.59	1895	0.86	7.49	1025	2920	2170	4200	6370
160	0.77	32.82	1990	0.92	6.57	965	2955	442	4740	5182
170	0.81	32.01	2020	0.925	5.65	835	2855	-1270	4920	3650
180	0.80	31.21	1930	0.86	4.79	665	2595	-3300	4420	1120
190	0.74	30.47	1770	0.79	4.00	506	2276	-4040	3400	-640
200	0.66	29.81	1550	0.69	3.31	373	1923	-4470	2680	-1790
210	0.54	29.27	1320	0.58	2.73	261	1581	-4030	1960	-2070
220	0.47	28.80	1110	0.47	2.26	178	1288	-3700	1320	-2380
230	0.38	28.42	900	0.34	1.92	113	1013	-3500	880	-2620
240	0.29	28.13	680	0.22	1.70	67	747	-3340	700	-2670

voltage is zero, which gives the greatest torque. This was done because the designer is interested in the worst condition that can happen. In the tests made, the instant of short circuit was controlled to give this worst condition. However, in operation very few of the short circuits will happen to occur at this particular point. In most cases the torque will be very small compared to the worst condition.

As has been stated the torque produced by a poly-phase short circuit in all cases thus far investigated is much less than the maximum torque resulting from a single-phase short circuit. The probability of a single-phase short circuit is also much greater than the probability of a polyphase short circuit. For these reasons practically all of the results given are for single-phase short circuits.

In the first part of this paper equations were derived for an "ideal machine," that is a machine to which the

A and B of Fig. 5 show this difference. The area under the two curves is the same since the maximum stored energy is the same but the rate of change of energy is very different, giving a corresponding difference in the value of peak torque.

It might be assumed that Equation (11), which gives the torque in terms of the currents during the short circuit and the voltage before the short circuit, could be applied to actual measured currents in cases where the self inductance of the separate circuits is not constant. However, the torque corresponding to a given current depends on the rate of change of inductance. For this reason this equation for torque is true only when the currents are varying as in the "ideal machine." For instance, if these equations are used with the values of current given by Curves A and C of

*Equations (40) and (41), *Short Circuits of Synchronous Machines*, (Reference 3).

Fig. 4, the torque obtained would be that for the given values of current but assuming that that current was varying at a rate given by the theoretical equations. The error corresponding to this assumption is shown by curve *C* of Fig. 5, which gives a maximum torque almost three times the actual value, whereas the torque calculated by the sem-graphical method agrees very closely with the measured torque.

It will be observed that all of the discussion has assumed a short circuit occurring when the machine is running on open circuit. This has been done to simplify the analysis and tests. It is evident that the short-circuit currents depend on the flux interlinkages at the instant of short circuit. The effect of the initial currents is to modify the initial flux. In the case of a single-phase machine operating at unity power factor, if a short circuit occurs at the instant of zero voltage, the load current is also zero so that this case is almost

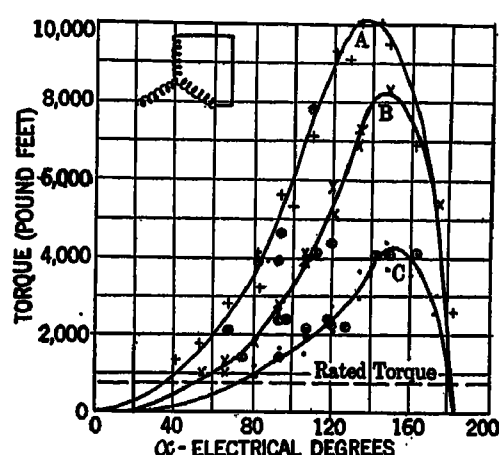


FIG. 7—SHORT-CIRCUIT TORQUE FOR VARIOUS FIELD CURRENTS

- A. Field current = 27 amperes giving 3240 volts during open circuit
 - + From magnetic accelerometer
 - ⊕ From flywheel and contact accelerometer
- B. Field current = 20 amperes giving 3010 volts
 - x From magnetic accelerometer
 - ⊙ From flywheel and contact accelerometer
- C. Field current = 10 amperes giving 2180 volts
 - From magnetic accelerometer
 - From flywheel and contact accelerometer

identical with the case of a short circuit during open circuit operations. In case the power factor is not unity, or for any case of polyphase operation, the solution is not quite as simple. However, in all cases the equations that have been derived apply equally well provided the proper correction is made for the different initial flux interlinkages.

An illustration of the dependence of the currents and torque on the initial interlinkage is given by the curves of Fig. 7. This shows the torque obtained experimentally for various initial values of field current. The generated voltage before the short circuit is a measure of the initial flux interlinkages of the armature. According to the theory developed, the torque should be proportional to the square of the initial flux. Of course, since saturation will increase the leakage, the field flux will increase somewhat faster than the armature flux as the field current is increased. Neglecting these effects the maximum torque should vary as the square of the generated voltage before the short circuit. If in Fig. 7 the peak torque for the two lower values of

field current be calculated from the test value for the maximum field current assuming a variation proportional to the square of the voltage, 8800 lb-ft. and 4600 lb-ft. are obtained as compared with 8250 and 4300 respectively from tests.

The curves of Fig. 7 also show that saturation is not a major factor in determining the short-circuit torque except that it must be considered in determining the initial flux. The two higher values of field current are well up on the saturation curve as shown by the fact that a 35 per cent increase in field current gives only an 8 per cent increase in voltage, and yet the torque can be calculated assuming that it varies with the square of the voltage with reasonable accuracy. This must not be taken as a proof that saturation will never be a major factor because it is entirely possible that in some cases a large proportion of the leakage flux may traverse a path having enough iron to make the effect of saturation appreciable, in determining the rate of change of stored energy.

Mr. Theo. Williamson conducted most of the tests referred to and his work is hereby acknowledged, as are the suggestions of Messrs. Fechheimer and Soderberg under whose supervision the work was done.

Appendix I

SYMBOLS

- T = Resultant torque produced by the reaction of the currents and fluxes. (Assumed positive when it tends to decrease the speed of rotation.)
- ω = Angular velocity of the rotor.
- t = Time (seconds).
- α = Angular position of the rotor. ($\alpha = 0$ is taken to be the position giving zero generated voltage).
- U = Stored magnetic energy of a circuit or system of circuits.
- I_f = Value of field current before the short circuit.
- I_A = Normal rated r. m. s. value of armature current.
- i_a, i_b , etc.—Denote the current in the circuit indicated by the subscript at any time t during the transient.
- i'_a, i'_b , etc.—In finding the stored energy, the current is assumed to vary from 0 to i_a or 0 to i_b . The symbol i' is used to distinguish a value of current during the assumed variation from an actual value i during the short circuit.
- ϕ_a, ϕ_b , etc.—Denote the resultant flux interlinkages of the phase denoted by the subscript.
- e_a, e_b , etc.—Denote the voltage generated during normal operation in the phase indicated by the subscript.
- E_A = Rated r. m. s. voltage per phase (*i. e.*, terminal to neutral).
- e_m = Open circuit peak voltage per phase (*i. e.*, terminal to neutral).
- L_a, L_f , etc.—Denote the self inductance of the circuit indicated by the subscript.

M_{ab}, M_{bf} , etc.—Denote the mutual inductance between the two circuits indicated by the subscripts.
 M_{AF} = Mutual inductance between phase a and the field winding at $\alpha = 0$.
 N_a, N_b , etc.—Number of turns in the circuit indicated by the subscript.
 n = Any integer.

$$K = \frac{M_{AF}}{\sqrt{L_a L_f}}$$

Appendix II

Calculation of Short Torque in an Ideal Machine. A machine to which the following assumptions apply is referred to as an ideal machine:

1. Resistance and saturation are negligible.
2. The self inductance of each winding is constant.
3. The mutual inductance between the field and each armature winding varies as the cosine of the angle between the field and armature winding considered.

For a Single-Phase Short Circuit. From Equation (36) in *Mechanical Forces Between Electric Circuits* by Karapetoff²

$$U = \frac{1}{2} [i_a^2 L_a + 2 i_a i_f M_{fa} + i_f^2 L_f]$$

From Equation (4)

$$T = \frac{dU}{d\alpha}$$

Under the actual condition of a short circuit, the flux is substantially constant and the current varies. The solution of this case is complicated mathematically. However, since the forces at any instant depend only on the fluxes and currents at that instant, the torque can be determined by the given currents and fluxes, but considering the current held constant for a differential movement of the rotor, *i. e.*, determine the derivative of U with respect to α when i is constant.

$$\frac{dU}{d\alpha} = \frac{1}{2} \left[i_a^2 \frac{dL_a}{d\alpha} + 2 i_a i_f \frac{dM_{af}}{d\alpha} + i_f^2 \frac{dL_f}{d\alpha} \right] \quad (5)$$

If L_a and L_f are constant, this reduces to

$$\frac{dU}{d\alpha} = i_a i_f \frac{dM_{af}}{d\alpha} \quad (6)$$

Since the effect of saturation is neglected, $\frac{dM_{af}}{d\alpha}$ can be determined from the no-load operation of the machine. Then

$$e_a = N_a \frac{d\phi_a}{dt} = e_m \sin \alpha \quad (7)$$

Where e_a is the voltage generated and is assumed to be sinusoidal, but during no-load operation,

$$N_a \phi_a = I_f M_{af} \quad (8)$$

Where I_f denotes the steady-state or open-circuit value of field current.

Differentiating (8)

$$N_a \frac{d\phi_a}{dt} = I_f \frac{dM_{af}}{dt} \quad (9)$$

substituting this value in Equation (7)

$$e_a = e_m \sin \alpha = I_f \frac{dM_{af}}{d\alpha}$$

$$\text{or, } \frac{dM_{af}}{d\alpha} = \frac{e_m \sin \alpha}{I_f \cdot \omega} = \frac{e_a}{I_f \cdot \omega} \quad (10)$$

Substituting in (6),

$$\frac{dU}{d\alpha} = T = \frac{i_f}{I_f \cdot \omega} \cdot i_a \cdot e_m \cdot \sin \alpha \quad (11)$$

Or, expressed in words, the torque is equal to the product of instantaneous value of armature current by the voltage that would have been generated under open-circuit conditions and this multiplied by the ratio of the instantaneous field current to the value of field current before the short circuit, and divided by the angular velocity.

B. Polyphase Short Circuit. For a polyphase short circuit, the equations for torque can be derived in a similar manner. From Equation (36) as given by Karapetoff²

$$U = \sum_u^n \frac{i_u}{2} \sum_v^n i_v M_{vu}$$

Therefore, differentiating with i constant

$$\frac{dU}{d\alpha} = \sum_u^n \frac{i_u}{2} \sum_v^n i_v \frac{dM_{vu}}{d\alpha} \quad (12)$$

For a three-phase short circuit and any given values of currents, constant self-inductance in each phase and constant mutual inductance between phases, but with the mutual inductance between the field and each phase variable

$$\frac{dU}{d\alpha} = i_a i_f \frac{dM_{af}}{d\alpha} + i_b i_f \frac{dM_{bf}}{d\alpha} + i_c i_f \frac{dM_{cf}}{d\alpha} \quad (13)$$

From Equation (10)

$$\frac{dM_{af}}{d\alpha} = \frac{e_m}{I_f \cdot \omega} \sin \alpha = \frac{e_a}{\omega \cdot I_f}$$

In a similar manner

$$\frac{dM_{bf}}{d\alpha} = \frac{e_b}{\omega \cdot I_f}$$

$$\frac{dM_{cf}}{d\alpha} = \frac{e_c}{\omega \cdot I_f}$$

Substituting these values in Equation (13).

$$\frac{dU}{d\alpha} = T = [i_a e_a + i_b e_b + i_c e_c] \frac{i_f}{\omega \cdot I_f} \quad (14)$$

Appendix III

In Appendix II, Equations (11) and (14) were derived giving the torque in an "ideal machine" in terms of the currents and rotor position. R. F. Franklin³ has derived equations for the current as a function of rotor position for the same "ideal machine." These values of current will be substituted in Equation (11) and Equation (14) to compare the torque for single-phase and three-phase short circuits.

Equations (7) and (8) for terminal-to-neutral single-phase short circuit in Franklin's paper are:

$$i_a = I_f \frac{M_{AF}}{L_a} \frac{1 - \cos \alpha}{1 - K^2 \cos^2 \alpha} \quad (15)$$

$$i_f = I_f \frac{1 - K^2 \cos \alpha}{1 - K^2 \cos^2 \alpha} \quad (16)$$

Substituting these values in Equation (11),

$$T = \frac{e_m I_f M_{AF} \sin \alpha}{\omega L_a} \frac{1 + K^2 \cos^2 \alpha - (1 + K^2) \cos \alpha}{[1 - K^2 \cos^2 \alpha]^2} \quad (17)$$

For the purpose of plotting the instantaneous short-circuit torque in terms of normal rated torque, it will be assumed that the machine is rated so that the peak value of unsymmetrical terminal-to-terminal (star-connected) short-circuit current is twelve times the rated r. m. s. current per phase. It will be assumed that

$$K = \frac{M_{AF}}{\sqrt{L_a L_f}} = 0.85$$

And that

$$L_f = L_a.$$

Then, from Equation (41) in Franklin's paper:

$$i_{u(max)} = 3.53 I_f \quad (18)$$

or,

$$I_a = 0.294 I_f$$

But the normal or rated torque is given by

$$\text{Rated power} = \omega T_N = 3 E_A I_A = 2.13 e_m I_A = 0.626 e_m I_f \quad (19)$$

Where E_A is the rated r. m. s. phase voltage (terminal to neutral) and I_A the rated r. m. s. armature current per phase.

Substituting (19) in (17) gives for a single-phase terminal to neutral short circuit

$$\frac{T}{T_N} = \frac{K^2 L_f}{0.626 M_{AF}} \frac{[1 + K^2 \cos^2 \alpha] - [1 + K^2] \cos \alpha}{[1 - K^2 \cos^2 \alpha]^2} \sin \alpha \quad (20)$$

This is plotted in curve A of Fig. 3 for the values of $K = 0.85$ and $M_{AF}/L_f = 0.85$ as assumed above.

The torque for a three-phase short circuit is given by Equation (14) as

$$\omega T = \frac{i_f}{I_f} [i_a e_a + i_b e_b + i_c e_c]$$

Since R. F. Franklin³ used the same assumptions as were used in deriving Equation (14) his values for cur-

rents will be used and are as follows (Equations (71), (72), (73), and (74) in his paper):

$$i_f = I_f \frac{1 - K^2 \cos \alpha}{[1 - K^2]} \quad (21)$$

$$i_a = \frac{2}{3} I_f \frac{M_{AF}}{L_a} \frac{(1 - 0.5 K^2) - \cos \alpha + 0.5 K^2 \cos 2 \alpha}{1 - K^2} \quad (22)$$

$$i_b = \frac{1}{-3} I_f \frac{M_{AF}}{L_a} \frac{(1 - 0.5 K^2) + 2 \cos (\alpha - 120) - K^2 \cos 2 (\alpha + 120)}{1 - K^2} \quad (23)$$

$$i_c = \frac{1}{-3} I_f \frac{M_{AF}}{L_a} \frac{(1 - 0.05 K^2) + 2 \cos (\alpha + 120) - K^2 \cos 2 (\alpha - 120)}{1 - K^2} \quad (24)$$

The corresponding values of e_a , e_b , and e_c are

$$e_a = e_m \sin \alpha \quad (25)$$

$$e_b = e_m \sin (\alpha - 120) \quad (26)$$

$$e_c = e_m \sin (\alpha + 120) \quad (27)$$

Substituting these values in Equation (14) gives

$$\omega T = \frac{I_f}{3} \frac{M_{AF}}{L_a} e_m \frac{(1 - K^2 \cos \alpha)}{(1 - K^2)^2} \{ [1 - 0.5 K^2] [2 \sin \alpha - \sin (\alpha - 120) - \sin (\alpha + 120)] - 2 [\cos \alpha \sin \alpha + \cos (\alpha - 120) \sin (\alpha - 120) + \cos (\alpha + 120) \sin (\alpha + 120)] + K^2 [\cos 2 \alpha \sin \alpha + \cos 2 (\alpha + 120) \sin (\alpha - 120) + \cos 2 (\alpha - 120) \sin (\alpha + 120)] \} \quad (28)$$

But combining terms and simplifying,

$$2 \sin \alpha - \sin (\alpha - 120) - \sin (\alpha + 120) = 3 \sin \alpha \quad (29)$$

and,

$$\cos \alpha \sin \alpha + \cos (\alpha - 120) \sin (\alpha - 120) + \cos (\alpha + 120) \sin (\alpha + 120) = 0 \quad (30)$$

and,

$$K^2 [\cos 2 \alpha \sin \alpha + \cos 2 (\alpha + 120) \sin (\alpha - 120) + \cos 2 (\alpha - 120) \sin (\alpha + 120)] = -\frac{3}{2} K^2 \sin \alpha \quad (31)$$

Substituting Equations (53), (54), and (55) in (52) gives

$$\omega T = \frac{I_f}{3} \frac{M_{AF}}{L_a} e_m \frac{1 - K^2 \cos \alpha}{(1 - K^2)^2} [(1 - K^2) 3 \sin \alpha] \quad (32)$$

Substituting the values of e_m from Equation (19) gives

$$\frac{T}{T_N} = \frac{M_{AF}}{0.626 L_a} \frac{1 - K^2 \cos \alpha}{1 - K^2} \sin \alpha \quad (32)$$

This is plotted as curve B of Fig. 3 to compare the torque from three-phase terminal to terminal and single-phase terminal to neutral short circuits.

Appendix IV

SEMI-GRAPHICAL CALCULATION OF TORQUE

1. *Neglecting Resistance.* The general method has been discussed and this appendix will merely give an actual example as an illustration. The current values for this example are taken from the oscillogram shown in Fig. 1. The generated voltage corresponding to the initial field current was 3240 volts (r. m. s.) at 60-

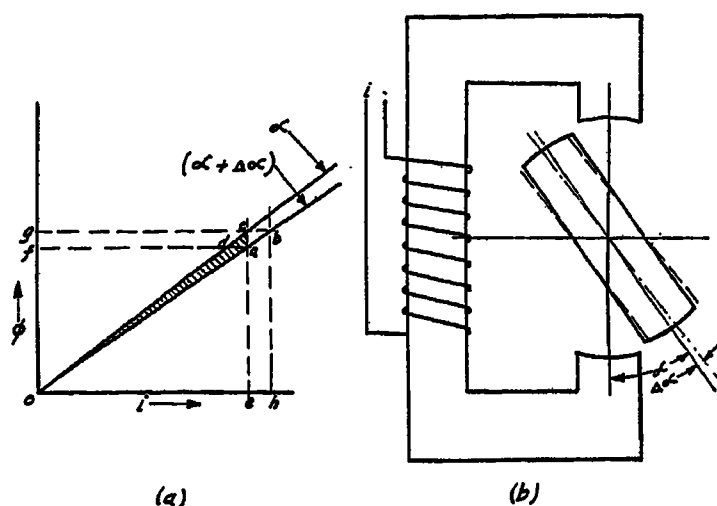


FIG. 8—DIFFERENTIAL CHANGE IN STORED ENERGY OF MAGNETIC CIRCUIT

cycle frequency. The flux interlinkages of the armature can be determined from this voltage,

$$e_{(volts)} = N \frac{d\phi}{dt} \times 10^{-8} \quad (34)$$

but $e = e_m \sin \omega t = 3240 \times 1.41 \sin \omega t$.

Substituting in (34) and integrating

$$-\frac{3240 \times 1.41}{\omega} \cos \omega t = N \phi \times 10^{-8}$$

$$\text{at } \omega t = 0 \quad N_a \phi_a \times 10^{-8} = 12.1$$

The initial interlinkages of the field winding calculated correcting for the ratio of the number of turns in the two windings and estimating the leakage flux gives $N_f \phi_f \times 10^{-8} = 37.5$.

These values of flux are used with the current values from the oscillogram to obtain the energy of the magnetic field. The successive values are tabulated in Table I. The calculated torque is plotted as curve C in Fig. 6. Then the torque in joules per electrical

radian is given by $\frac{\Delta U}{\Delta \alpha}$. Since the generator under

consideration is a six-pole machine, the torque in lb-ft.

$$\text{is given by } 3 \times 0.7376 \frac{\Delta U}{\Delta \alpha} = 2.21 \frac{\Delta U}{\Delta \alpha}.$$

2. *Calculation Considering Resistance.* The two effects of resistance to be calculated are:

1. The change in flux interlinkages of each circuit, and

2. The power represented by the resistance losses. The change in flux interlinkages is given by

$$R i = e = N \frac{d\phi}{dt} = 10^{-8}$$

or

$$R i \Delta t = 10^{-8} \times N \Delta \phi$$

This is calculated for each increment of time. The initial value of flux has been calculated. Starting with the initial value and subtracting the successive values of decrease in flux gives the flux at any instant which is then multiplied by the corresponding value of current to get the stored energy. The calculation of power represented by resistance loss needs no explanation, except that in these calculations a correction was made for the change in speed of the rotor produced by the torque acting on it.

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Discussion

R. F. Franklin: Mr. Penney's paper reveals another interesting practical application of the constant-leakage theorem which R. E. Doherty called to the attention of the Institute a number of years ago. This theorem has been used extensively in the investigation of short-circuit phenomena in a-c. apparatus. It was this theorem that I used in the investigation of the short-circuit currents of synchronous machines referred to by the author. The ultimate goal of that investigation was a determination of the torque and forces acting during short circuit of synchronous machines, because of the importance of a knowledge of these forces in the design and construction of alternators. The investigation was completed and formulas giving the torque acting under various conditions of short circuit obtained. These formulas are now being used in the design of synchronous machines. The method used in obtaining these formulas has been presented to the Institute in a paper by Doherty and Park, referred to by Mr. Penney in his bibliography, and is essentially the same as that used by Mr. Penney.

An important contribution by the author is the step-by-step calculation of torque from the current oscillograms which takes into consideration the effect of resistance.

May I again emphasize the importance of the constant-leakage theorem in the solution and explanation of short-circuit problems and commend a thorough knowledge of it to all engineers interested in this phase of engineering.

C. J. Fechheimer: Mr. Penney brings forcibly to our attention the importance of the mechanical problems in electrical machinery. Most designers have concerned themselves more

with the electrical problems and have frequently left to the draftsman the important mechanical problems. Fortunately, in manufacturing companies mechanical experts are now coming to the front.

There have been mechanical failures of machines which have not been understood largely because we had no analytical method of understanding or attacking the problems involved. Not very long ago castings were used extensively and such castings occasionally failed, probably largely because the rewere high shrinkage stresses. They were then made heavier, whereas they may have been heavier at the outset than was necessary.

Mr. Penney's able work was not only experimental as was recorded in his earlier paper, but now he has completed the theoretical analysis as well.

In the inclusion of resistance in the solutions, he has made a noteworthy contribution as that is one of the things that makes such calculations difficult.

B. A. Behrend: The contribution of Mr. Doherty which Mr. Franklin mentioned is, in my opinion, one of the outstanding papers on sudden short circuits of electrical machinery. The way in which Mr. Penney has made use of Mr. Doherty's contribution, is another instance of its great value.

A. B. Field: Mr. Penney has pointed out that in discussing these short-circuit torques we must recognize different values of torque in the various parts of the structure; the torque on the stator windings will be greater than the torque upon the shaft, and we have again quite another value of torque upon the end-ring of the rotor in the case of a turbo generator. In some of the early machines running at 3600 rev. per min., we used occasionally to get a journal or coupling extension slightly twisted after a very heavy short circuit. Those machines had a high short-circuit ratio and, as Mr. Penney has pointed out, the corresponding torques would be very great on a single-phase short circuit. It is the practise of some firms to provide against such possibilities by designing the coupling bolts so that they will shear before injury is done to the journal.

Mr. Penney is to be congratulated upon obtaining such close agreement between some of his calculated and experimental results.

G. W. Penney: I was very glad that Mr. Field pointed out that the torque to be resisted by the structural parts of the stator is usually much greater than the torque transmitted by the shaft because the stator is usually quite rigidly mounted. As an illustration of the importance of the rigidity of such parts I should like to mention a case in which the frame-shifting device of a frequency-changer set gave the stator considerable torsional flexibility. In this case the frame-shifting device was supported by structural-steel members and if the force corresponding to full short-circuit torque could act on these structural supports they would be seriously distorted. However, calculations showed that there was sufficient flexibility so that for a short circuit giving a peak value of torque 20 times normal, the maximum torque acting on the frame shifting device was less than 1.5 times normal. In a case such as this it would be quite possible that a careless attempt to strengthen the parts would result in stiffening the parts so that the stresses would be seriously increased rather than decreased. This illustrates the necessity of knowing the torque-time curve and the flexibility of the parts rather than merely designing parts to withstand an arbitrary value of torque.

One other point of importance is that a short circuit at the instant of zero voltage gives the highest torque while if the transient starts at the maximum voltage point the torque is very slight. For this reason the fact that a machine has withstood one short circuit or even several is no proof that it will withstand another unless the voltage at the instant of short circuit is known. For example, in the first tests for measuring this torque no device for controlling the instant of short circuit was used and twenty tests were made before one was obtained within 30 degrees of the instant of zero voltage, although of course by the theory of probability it should have occurred much sooner.

Analytical Determination of Magnetic Fields

Simple Cases of Conductors in Slots

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and

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Synopsis.—In this paper La Place's and Poisson's equations are applied to cases of current carrying conductors in rectangular slots to show the flux distributions which obtain.

The paper first treats with the general case which is a single conductor, completely surrounded by insulation, at the bottom of a slot. Next is taken up the more practical case of a slot containing two insulated conductors, one above the other, in which currents of equal magnitude are considered first to flow in the same direction, and then in opposite directions.

In addition to these analyses, a few special cases are discussed. Methods are also discussed by which the flux distributions in slots containing an even number of coil sides may be obtained, or in slots

the conductors of which carry currents not in time-phase. Equations are developed from which all of these fields can be calculated.

A discussion is included to show the distribution of flux on the assumption that the lines go straight across the slot, and a comparison is made between the slot inductance determined mathematically from the developed equations and by the usual design formulas. In the case considered it is found that the design formulas give a value of slot inductance which is about 96 per cent of that obtained by the mathematical treatment which is within limits of engineering accuracy. An expression is developed which shows the error that may be expected in any particular case.

* * * * *

I. INTRODUCTION

IN the last few years several papers have been presented before the Institute and articles have been published in various technical journals on the theory and practical application of flux plotting. It has been shown that quite accurate flux plots can readily be made free hand for many geometrical figures, if they are void of current, about the only fundamental requirement being a knowledge of the potential difference between the various boundaries of the configuration. Although the problem is greatly complicated in current carrying regions, methods have been outlined for free hand mapping of fields under these conditions, and can be applied very well whenever the general arrangement of the lines of force is known in advance. If the general field arrangement is unknown, then a great deal of sketching and resketching must be done in order to obtain a correct plot, and often much labor can be saved by deriving analytically the equations for the lines of force and then plotting the loci of these equations.

Several years ago W. Rogowski solved La Place's and Poisson's equations for the case of a pancake type transformer, analytically determining the magnetic field distribution about the windings. An excellent translation of Rogowski's work was given by Dr. A. R. Stevenson, Jr.,¹ in 1926. Shortly after that Messrs. Stevenson and Park² showed the application of the analytical method of determining the flux distribution about the field pole of a definite pole machine, including in their discussion several other figures which are of theoretical interest. Cases of conductors in slots have also been treated with,³ but there the solution

results in a series which converges so slowly that the task of plotting the field is laborious.

In this paper analytical expressions are developed for plotting the flux about rectangular conductors in rectangular slots, by use of the method originally employed by Rogowski. Flux plots are shown for a number of different locations of a single conductor in a slot, and for the practical case of two conductors, one above the other in the same slot. The mathematical expressions are in the form of a series that converges very rapidly, thus simplifying the problem of making the plots.

In addition to the above, a comparison is made between the slot inductance determined: (a), by the usual design formulas; (b), by mechanically integrating the mathematical flux plot to obtain the flux linkages, and (c), directly from the R -equations.

From the latter a simple expression is obtained for use in design formulas to give the increase in inductance due to the curvature of the flux lines over the inductance determined on the usual assumption that the lines of force are everywhere parallel to the bottom of the slot.

II. FUNDAMENTAL EQUATIONS

Consider the general example shown in Fig. 1, which represents an insulated rectangular conductor at the bottom of an infinitely deep slot. It is assumed that:

1. The permeability of the air, insulation, and copper is unity.
2. The permeability of the iron is infinite. (These two assumptions mean that the flux must enter the iron at right angles to the surface.)
3. The conductors are subdivided, thus eliminating skin effects and resulting in uniform current density.

Rogowski developed the conception of dividing the slot into regions satisfying either LaPlace's or Poisson's equations; then, by considering each region separately, the current distribution may be represented by a single dimension Fourier series, and the problem greatly

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1. For references see Bibliography.

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simplified.* The single dimensional Fourier series may be chosen to represent the current in the one slot only, but another simplification is made possible from the application of the method of images.

It is well known that with a conductor near an iron surface of infinite permeability it is possible to replace the iron surface by a conductor, called the image of the first, carrying current in the same direction. Similarly, a slot may be replaced by its image on both sides and below, see Fig. 2, the first group of images being

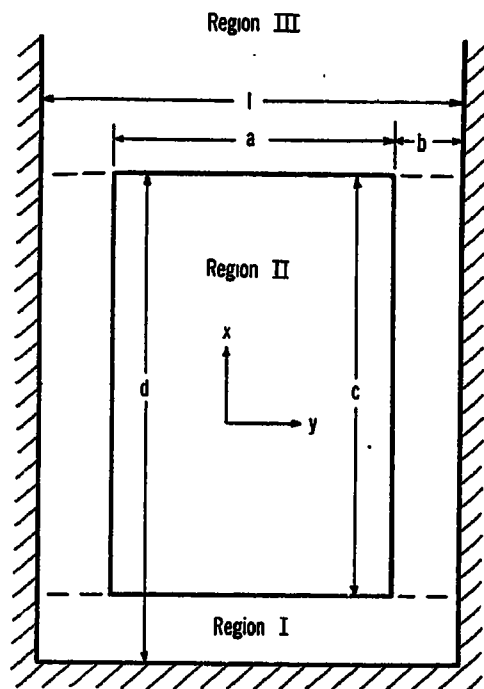


FIG. 1—GENERAL CASE OF CONDUCTOR COMPLETELY INSULATED FROM SLOT

reimaged, etc. Due to the fact that the slot is open at the top only a double row of images exists, which then replaces the original conductor and slot, and gives rise to a periodic rectangular current distribution, the Fourier series of which can readily be obtained.

The total field of the slot of Fig. 1 is divided into three distinct regions:

Region I. Air district between the images formed by the bottom of the slots and the bottom of the conductors.

Region II. District occupied by the conductors in a horizontal row including the air or insulation spaces between the conductors.

Region III. The air and insulation space above the conductors.

Region I, having no currents, satisfies Laplace's equation,

$$\frac{\partial^2 R}{\partial x^2} + \frac{\partial^2 R}{\partial y^2} = 0 \quad (1)$$

Region II, being a district of currents, must satisfy Poisson's equation,

$$\frac{\partial^2 R}{\partial x^2} + \frac{\partial^2 R}{\partial y^2} = -4\pi I \quad (2)$$

*Herein lies the main difference between the present analysis and that of E. Roth, reference 5. He used a two dimensional Fourier Series.

Equations (1) and (2) are the fundamental differential equations for magnetic fields. R is the vector potential of the magnetic field and is defined by the relations,

$$\left. \begin{aligned} X &= \frac{\partial R}{\partial y} \\ Y &= -\frac{\partial R}{\partial x} \end{aligned} \right\} \quad (3)$$

X and Y being the x and y components of the magnetic field intensity in the slot.

As pointed out in Stevenson's translation, the slope of a line of force is

$$\frac{dy}{dx} = \frac{Y}{X} = -\frac{\frac{\partial R}{\partial x}}{\frac{\partial R}{\partial y}} \quad (4)$$

and hence lines of force and corresponding lines representing constant values of R have the same slope at every point. Therefore, by solving Equations (1) and (2) for R in terms of the coordinates x and y , it is possible to plot the flux field because lines of constant R become lines of force. Differences in R are differences in flux, the numerical value between two lines of R representing the flux within that region. See Appendix A for a discussion of the properties of R .

The current density I must be represented mathematically. This is done as follows: Commencing at the left hand side of the slot, Fig. 1, and passing to the right, the current density is zero until the conductor is

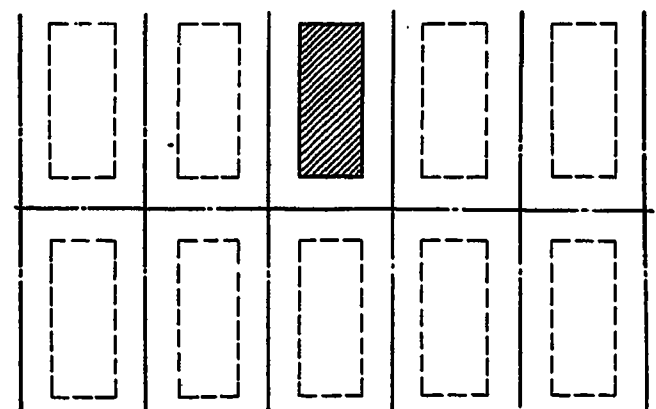


FIG. 2—IMAGES OF A CURRENT CARRYING CONDUCTOR IN AN INFINITELY DEEP SLOT IN IRON

reached. There the current density jumps to a value i determined by the total current in the conductor and the cross-sectional area of the copper. It is assumed that the total current is coming out of the paper towards us, bringing in the negative sign of Equation (2). The current density continues constant to the other side of the conductor, where it drops back to zero, and then continues zero to the other side of the slot. For the slots on either side the same distribution holds. This gives rise to the periodic repeating current distribution

shown in Fig. 3. It may be represented by a Fourier series of the form:

$$I = \frac{1}{2} \alpha_0 + \alpha_1 \cos k y + \dots + \alpha_n \cos n k y \quad (5)$$

where $k = \frac{2\pi}{l}$, $l = a + 2b$; see Fig. 1.

The value of the coefficient α_n may be determined from the general integral

$$\alpha_n = \frac{2}{l} \int_{-a/2}^{a/2} i \cos n k y dy = \frac{4i}{n k l} \sin \frac{n k a}{2} \quad (6)$$

for, $n = 1, 2, 3, \dots$
For $n = 0,$

$$\alpha_0 = \frac{2}{l} \int_{-a/2}^{a/2} i dy = \frac{2a}{l} i \quad (7)$$

The Fourier series for I then becomes

$$I = \frac{a i}{l} + \sum_{n=1}^{\infty} \frac{4i}{2\pi n} \sin \frac{n\pi a}{l} \cos n k y \quad (8)$$

From a general knowledge of the solution of partial differential equations, and the physics of the particular

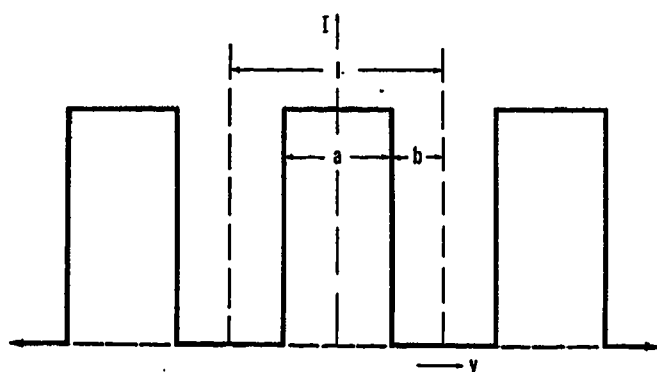


FIG. 3—CURRENT DENSITY CURVE FOR FOURIER SERIES

problem treated, it will be assumed that the function R of Equations (1) and (2) is of the form

$$R = R_0 + R_1 \cos k y + \dots + R_n \cos n k y \quad (9)$$

where $R_0 \dots R_n$ are functions of x alone and must be determined from the boundary conditions.

Substituting for R in Equations (1) and (2) the following sets of relations are obtained,

$$\left. \begin{aligned} \frac{d^2 R_0}{dx^2} &= 0 \\ \frac{d^2 R_1}{dx^2} - k^2 R_1 &= 0 \\ &\vdots \\ \frac{d^2 R_n}{dx^2} - n^2 k^2 R_n &= 0 \end{aligned} \right\} \quad (1b)$$

$$\left. \begin{aligned} \frac{d^2 R_0}{dx^2} &= -2\pi \alpha_0 = \frac{-4\pi a i}{l} \\ \frac{d^2 R_1}{dx^2} - k^2 R_1 &= -4\pi \alpha_1 \\ &\vdots \\ \frac{d^2 R_n}{dx^2} - n^2 k^2 R_n &= -4\pi \alpha_n \end{aligned} \right\} \quad (2b)$$

These equations have the solutions,

$$\left. \begin{aligned} R_0 &= \beta_0 + \beta_0' x \\ R_1 &= \beta_1 e^{kx} + \beta_1' e^{-kx} \\ &\vdots \\ R_n &= \beta_n e^{nkx} + \beta_n' e^{-nkx} \end{aligned} \right\} \quad (1c)$$

$$\left. \begin{aligned} R_0 &= \gamma_0 + \gamma_0' x + \gamma_0'' x^2 \\ R_1 &= \gamma_1 e^{kx} + \gamma_1' e^{-kx} + \frac{4\pi \alpha_1}{k^2} \\ &\vdots \\ R_n &= \gamma_n e^{nkx} + \gamma_n' e^{-nkx} + \frac{4\pi \alpha_n}{n^2 k^2} \end{aligned} \right\} \quad (2c)$$

of which the various integration constants must now be determined for the different regions.

Knowing the shape of the final solution, Equation (9), there are, for the three regions

Region I:

$$R = A_0 + A_0' x + (A_1 e^{kx} + A_1' e^{-kx}) \cos k y + \dots + (A_n e^{nkx} + A_n' e^{-nkx}) \cos n k y \quad (10)$$

Region II:

$$\begin{aligned} R &= B_0 + B_0' x + B_0'' x^2 \\ &+ \left(B_1 e^{kx} + B_1' e^{-kx} + \frac{4\pi \alpha_1}{k^2} \right) \cos k y + \dots \\ &+ \left(B_n e^{nkx} + B_n' e^{-nkx} + \frac{4\pi \alpha_n}{n^2 k^2} \right) \cos n k y \end{aligned} \quad (11)$$

Region III:

$$\begin{aligned} R &= C_0 + C_0' x \\ &+ (C_1 e^{kx} + C_1' e^{-kx}) \cos k y + \dots \\ &+ (C_n e^{nkx} + C_n' e^{-nkx}) \cos n k y \end{aligned} \quad (12)$$

III. DETERMINATION OF THE CONSTANTS

The above expressions form the general solution of the problem. It is now necessary to evaluate the constants from the boundary conditions. These are:

(a) At the bottom of the slot, coordinate $x = 0$, $Y = -\partial R / \partial x = 0$, as the flux must enter the iron at right angles.

Obtaining Y from Equation (10) and equating coefficients,

$$A_0 = 0, A_1 = A_1', \dots, A_n = A_n'$$

(b) At the boundary between Regions I and II, coordinate $x = d - c$, $X = \partial R / \partial y$, and $Y = -\partial R / \partial x$ are continuous since there is no refraction. Also at this boundary the constants of Equations (10) and (11) must be equal.

Therefore,

$$B_0' = -2 B_0'' (d - c)$$

$$A_0 = B_0 + B_0' (d - c) + B_0'' (d - c)^2$$

$$A_n [\epsilon^{nk(d-c)} - \epsilon^{-nk(d-c)}] = B_n' \epsilon^{nk(d-c)} - B_n' \epsilon^{-nk(d-c)}$$

and

$$A_n [\epsilon^{nk(d-c)} + \epsilon^{-nk(d-c)}] = B_n \epsilon^{nk(d-c)} + B_n' \epsilon^{-nk(d-c)} + \frac{4 \pi \alpha_n}{n^2 k^2}$$

(c) Relations similar to (b) hold at the boundary between Regions II and III, coordinate $x = d$, giving

$$C_0' = B_0' + 2 B_0'' d$$

$$B_0 + B_0' d + B_0'' d^2 = C_0 + C_0' d$$

$$B_n \epsilon^{nkd} - B_n' \epsilon^{-nkd} = C_n \epsilon^{nkd} - C_n' \epsilon^{-nkd}$$

$$B_n \epsilon^{nkd} + B_n' \epsilon^{-nkd} = C_n \epsilon^{nkd} + C_n' \epsilon^{-nkd} - \frac{4 \pi \alpha_n}{n^2 k^2}$$

(d) For large values of x the flux goes straight across the slot, so

$$X = \partial R / \partial y = 0, \text{ and}$$

$$Y = -\partial R / \partial x = \text{constant.}$$

Then $C_1, C_2, \dots, C_n$ all must equal zero as the terms in which they are included must vanish for large values of x .

(e) The terms in the regional equations that contain $\cos n k y$ give the curvature to the lines of flux. The other terms are the only ones extant at very large values of x , so must be the flux on the assumption that the lines of force go straight across the slot. So at the top of the conductor, $x = d$, from Equation (2b), Appendix B

$$\pi \alpha_0 c^2 = C_0 + C_0' d$$

Solving these groups of relations simultaneously, all constants but A_0 are readily determined. If the absolute value of R were known at any point it would be possible to evaluate A_0 , but since R is not known in any region A_0 can only be given an assumed value, say zero. This is justifiable since it is the differences of R which are desired primarily.

The constants thus become:

$$A_0 = 0 \text{ (assumed)}$$

$$A_0' = 0$$

$$A_n = A_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d-c)} - \epsilon^{-nkd}]$$

$$B_0 = -\pi \alpha_0 (d - c)^2$$

$$B_0' = 2 \pi \alpha_0 (d - c)$$

$$B_0'' = -\pi \alpha_0$$

$$B_n = \frac{-2 \pi \alpha_n}{n^2 k^2} \epsilon^{-nkd}$$

$$B_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d-c)} - \epsilon^{-nkd} - \epsilon^{nk(d-c)}]$$

$$C_0 = \pi \alpha_0 (2 c d - c^2)$$

$$C_0' = -2 \pi \alpha_0 c$$

$$C_n = 0$$

$$C_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} + \epsilon^{nkd} - \epsilon^{-nkd}]$$

(13)

The regional equations are obtained by substituting these constants in Equations (10), (11), and (12).

Region I:

$$R = \sum_{n=1}^{\infty} A_n (\epsilon^{nkx} + \epsilon^{-nkx}) \cos n k y \quad (14)$$

Region II:

$$R = -\pi \alpha_0 (d - c)^2 + 2 \pi \alpha_0 (d - c) x - \pi \alpha_0 x^2 + \sum_{n=1}^{\infty} \left(B_n \epsilon^{nkx} + B_n' \epsilon^{-nkx} + \frac{4 \pi \alpha_n}{n^2 k^2} \right) \cos n k y \quad (15)$$

Region III:

$$R = \pi \alpha_0 (2 c d - c^2) - 2 \pi \alpha_0 c x + \sum_{n=1}^{\infty} C_n' \epsilon^{-nkx} \cos n k y \quad (16)$$

IV. PLOTTING THE FIELD

With R a function of both x and y , it is convenient to first draw curves of R as a function of either variable

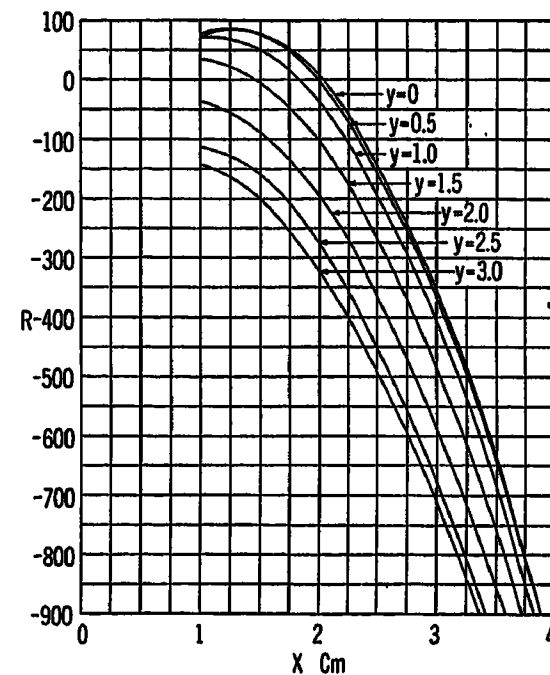


FIG. 4—AUXILIARY CURVES OF R AGAINST x , PARAMETER y FOR GENERAL CASE SHOWN IN FIG. 6

with the second variable as the parameter. In some cases, for instance plotting the field in detail about the kernel, or point upon which all flux lines apparently collapse, both sets of parametric curves are required for accuracy. The general example illustrated in this paper makes use of Figs. 4 and 5 in which R is plotted as a function of x for constant values of y .

From these auxiliary curves, lines of $R = \text{a constant}$ are chosen and the various coordinates then easily obtained from the graphs. The final plot of the magnetic field about the conductor insulated from the slot on all sides is given by Fig. 6. It was not found necessary to go above the second harmonic in order to secure fairly accurate calculations. This greatly simplified the numerical work. The following data, including the

dimensions of the slot and conductor, accompany the map.

$a = 4$ cm., $b = 1$ cm., $c = 6$ cm., $d = 7$ cm., $i = 30$ abamperes per sq. cm.

In reference to the auxiliary curves of Figs. 4 and 5 a few interesting points should be noted. These graphs show both positive and negative values of R . This does not indicate that flux is going in two directions about the kernel, for the differences in R are always negative, the direction of the flux being counter clock-

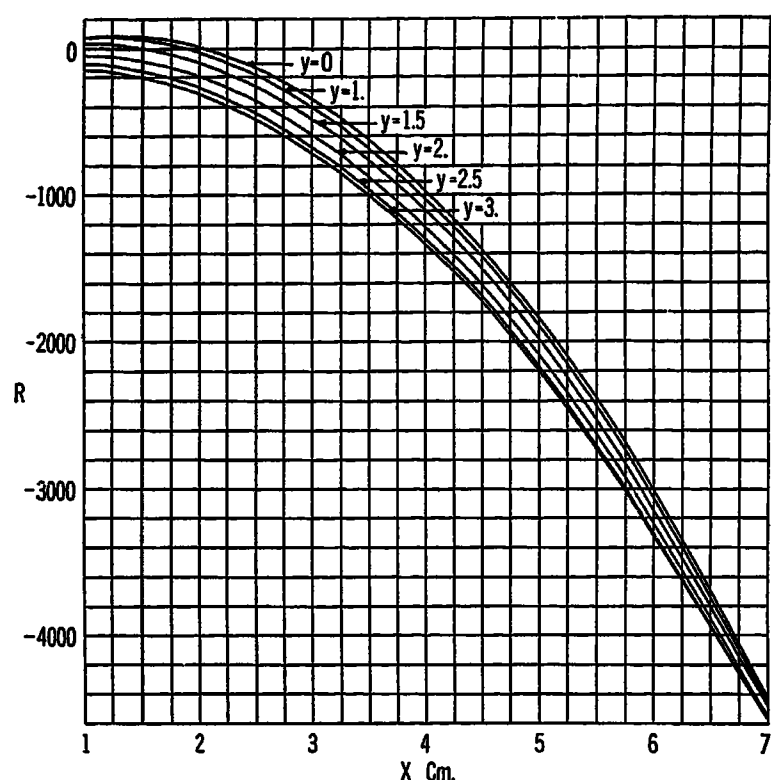


FIG. 5—AUXILIARY CURVES OF R AGAINST x , PARAMETER y , FOR GENERAL CASE SHOWN IN FIG. 6

wise, as shown by the auxiliary curves and as reasoned by the right hand rule. It will be remembered that the constant A_0 was assumed zero in lieu of its actual value which could not then be determined. If A_0 could have been correctly determined numerically, the $R = 0$ line would become a point, the location of the kernel. Only negative values of R would then appear on the auxiliary curves.

The final graph, Fig. 6, shows values of flux which are negative only, the $R = 0$ line being purposely pushed back to the kernel by adding negative flux of amount equal to the positive flux which was originally found.

It will also be noted from Fig. 5 that the curves tend to merge into a single line. This means that the lines of force become straighter as x increases. Theoretically, lines of R would cross the slot straight at infinity, but practically their curvature can not be noticed much above the top of the conductor.

It is good practise always to make a rough check on any problem when possible. In this particular case a check is made on the density of the flux crossing the slot a little above the conductor. The total current in the slot is 72 abamperes which gives an m. m. f. of 288 gilberts. The path reluctance per square centimeter is 6, hence the flux crossing the slot is 151 lines

per sq. cm. On the graph this value is obtained and the accuracy of the work is thus determined as far as flux density is concerned.

Likewise, a check is made on the actual total flux crossing the slot, the numbers to the right of Fig. 6 indicating the flux up to that point calculated on the assumption that the lines go straight across the slot. It is distinctly noticeable that such an approximation gives less flux near the bottom of the slot than is obtained by the more correct method. To compensate for the increased flux at the bottom of the slot when determined by Rogowski's method, there is, however, a greater density in lines in the other case as one moves up the slot. Near the top of the conductor, the difference in total flux calculated in the two manners is very small, and directly above the conductor the difference is negligible. As previously pointed out, the two lines of R equal to the same definite value tend to coincide, and on this basis the application of Rogowski to slots of finite depth is justified.

The method of calculating the flux upon the assumption that the lines have no curvature is contained in Appendix B.

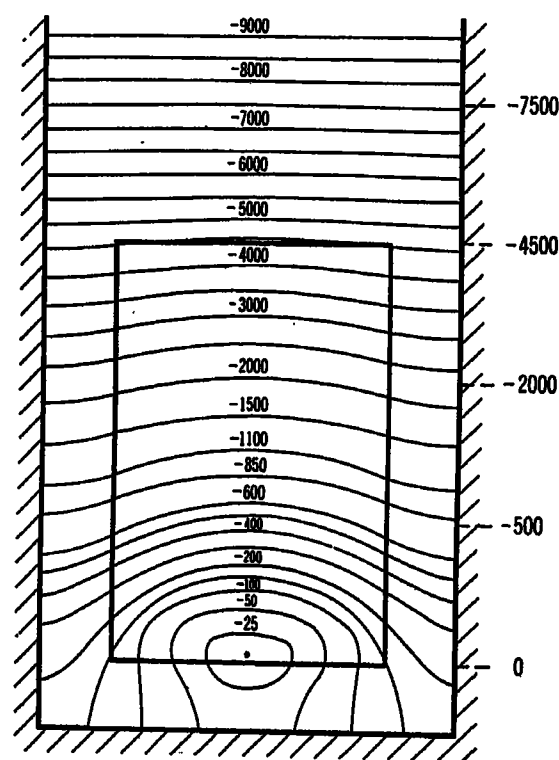


FIG. 6—FLUX ABOUT CONDUCTOR OF GENERAL CASE

V. SPECIAL CASES

The foregoing treatment considers the purely general case in which the conductor does not touch the slot at any point. The kernel is therefore inside the copper, as shown by Fig. 6, and as would be definitely determined by free hand graphical methods of plotting the magnetic field. The higher the conductor in the slot, the nearer does the kernel approach the geometric center of the conductor, the limit being the instance in which the slot is without a bottom.

Conversely, the nearer the copper approaches the bottom of the slot, with equal air-gaps between the sides of the conductor and the slot walls, the nearer

does the kernel approach the middle of the lower face of the conductor. This limiting case is shown in Fig. 7. The general equations of R , and the auxiliary curves from which these flux lines were plotted, are contained in Appendix C to which the reader is referred.

In calculating the flux upon the assumption that it goes straight across the slot, the height and total current of the conductor are the major factors concerning the

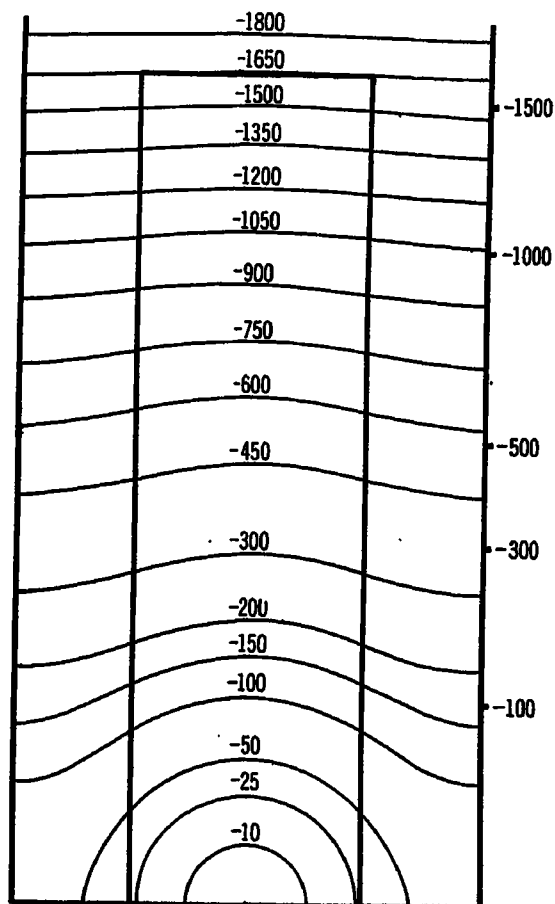


FIG. 7—FLUX FIELD ABOUT A CONDUCTOR WHICH TOUCHES THE BOTTOM BUT NOT THE SIDES OF THE SLOT

conductor itself. Of course, the current density depends upon both of the copper dimensions, but the width of the copper for a given total current has no effect upon the flux distribution, as it distinctly has in the two previous cases.

The conductor then might just as well extend clear across the slot, see Fig. 8. Of interest here is the fact that to leave no air space between the sides of the copper and the iron seemingly shifts the kernel from a point within the current carrying region to infinity below the conductor. No matter how small the air space may be, just as long as it is not zero, the kernel is still on the plot. But when the air space becomes zero, the kernel loses its identity on the field map.

Dr. Stevenson has suggested a simple figure to show physically why this may be true. The scheme has practical value as well as academic interest for it can be applied in other cases to determine the location of the kernel. It is therefore included in this paper.

Fig. 9 shows an iron cylinder enclosed by a concentric current carrying conductor. The lines of no work all converge at the center of the two cylinders. Now consider the sector between the two lines of no work given in the sketch. By the method of images, these lines of no work may be replaced by an iron surface,

thus excluding the rest of the current region, Fig. 10 resulting. Since the kernel is at the center of the circular sector, if the radius is made infinite, the kernel moves to infinity, giving the slot and conductor of Fig. 11. This is exactly Fig. 8.

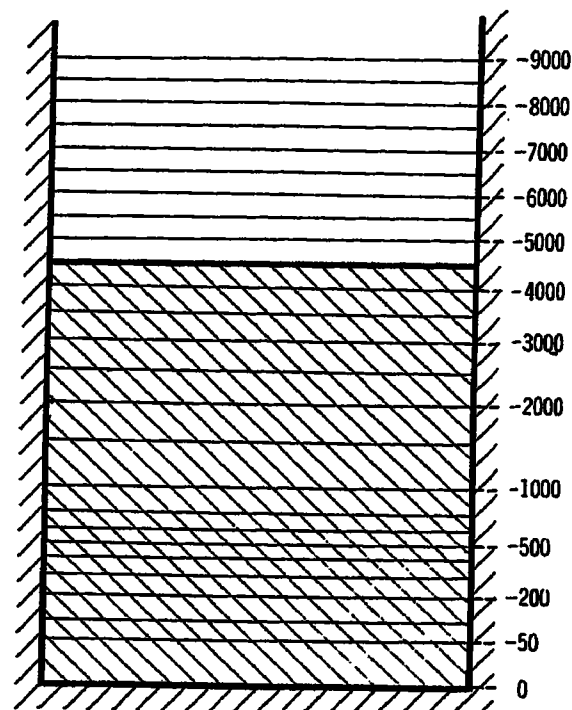


FIG. 8—FIELD ABOUT CONDUCTOR COMPLETELY FILLING SLOT

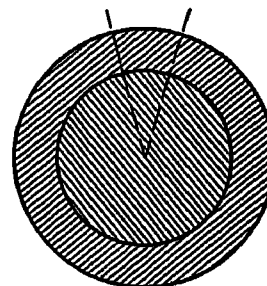


FIG. 9—COPPER CYLINDER WITH IRON CORE

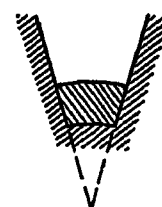


FIG. 10—EQUIPOTENTIAL SURFACES OF FIG. 9

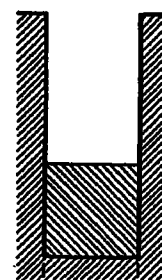


FIG. 11—MODIFICATION OF FIG. 10

The conductor under discussion is contained in what was formerly Region II. It is then noted, that substituting the condition of $d = c$ in the terms of Equation (11), only one term remains, *i e.*, $B_0'' x^2$ which is $-\pi \alpha_0 x^2$. This result definitely states that flux passes across the slot only in lines parallel to the lower face of the conductors, mathematically showing that the kernel is at infinity. Although this point may appear

academic, it is nevertheless of interest for the proper location of a kernel in a field plot is often a problem of importance.

VI. SLOT WITH TWO CONDUCTORS

The slot containing two conductors, completely insulated from each other and from the iron walls of the slot, and placed one above the other, is typical of synchronous machine design and therefore forms one

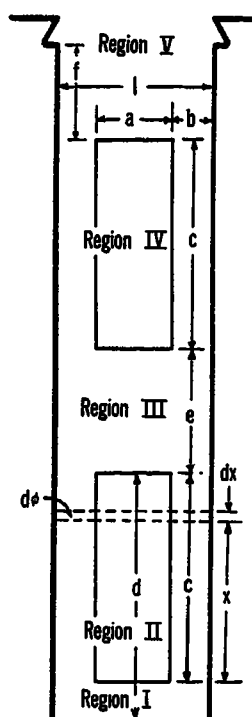


FIG. 12—SLOT WITH TWO CONDUCTORS

of the most practical applications of flux plotting by the mathematical method.

In the solution of this problem the entire field is divided into five regions, see Fig. 12. As before,

Region I: Air district between the images formed by the bottom of the slots and the bottom of the lower conductors.

Region II: District occupied by the lower conductors in a horizontal row, including the air or insulation spaces between the sides of the lower conductors.

Region III: The air and insulation space between the upper and lower conductors.

Region IV: District occupied by the upper conductors in a horizontal row, including the air or insulation spaces between the sides of these conductors.

Region V: The air and insulation space above the upper conductors.

The air regions satisfy Laplace's equation, Equation (1), and the current carrying regions satisfy Poisson's equation, Equation (2).

In the general case previously discussed, it is obvious that the magnetic field for the single conductor in any certain configuration will always yield one type of plot. Its form will be altered only by slot and copper dimensions, but will not be affected by the magnitude of the current. The direction of flow of the current will, of course, change the direction of the lines of flux.

The solution of this problem, however, brings into consideration the direction of the flow of current in the

conductors, that is, whether or not the current in the upper coil side is flowing in the same direction as the current in the lower coil side. Furthermore, the relative magnitudes of these currents are important, because for each ratio of the two densities there exists a distinct field. An infinity of flux plots is thus the complete answer to the problem. Although any one of these plots can be accurately determined, it is only within the scope of this paper to fully discuss two important types and to indicate the solution for any other set-up.

The illustration first treated with here is that in which the two conductors carry equal currents in the same direction. Similar to Fig. 2, the current carrying regions will now be represented by two infinite series of reflected and rereflected images, one above the other. Each region has its own Fourier series for the current density, and since the density is the same for each group of images, the Fourier series is thus the same for each region and is of the form given by Equation (8).

The form of the function R is as it was before, and from its substitution in Equations (1) and (2) are obtained the two sets of relations given by Equations (1b) and (2b). The first set of relations now holds for Regions I, III, and V, since they carry no current, while the second group holds for Regions II and IV, the current carrying districts. The general solutions for R ,

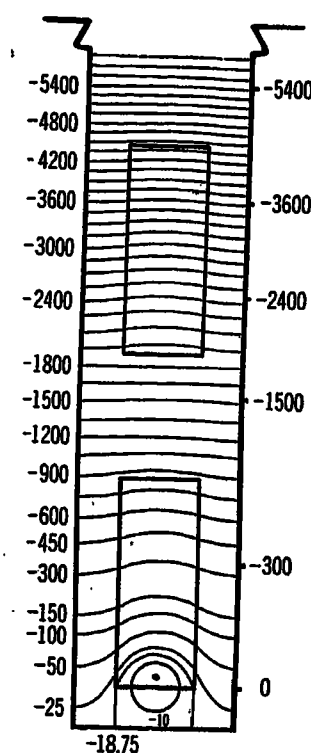


FIG. 13—FIELD ABOUT A TWO-CONDUCTOR SLOT
Currents in the conductors equal and in the same direction

and the constants for these equations, are obtained in like manner to the ones detailed in Section II of the paper. It is necessary now to solve simultaneously the five sets of regional solutions in order to determine the coefficients $A_0, A_n, \dots$ etc. The reader is referred to Appendix D for the complete mathematical analysis.

It is interesting to note that only one kernel appears in Fig. 13. But it is also noticeable that the flux through the lower part of the upper conductor shows considerable curvature, indicating a disturbance which is caused

by the kernel that conductor would have if acting alone. The total m. m. f. of the lower conductor is acting to send flux in a counterclockwise direction across the slot, while near the lower face of the upper conductor the m. m. f. of this current acts to send flux in a clockwise direction across the slot. The latter m. m. f., however, is very weak within this small interval, and the stronger m. m. f. predominates to the extent that any second kernel is wiped out.

The numbers to the right of Fig. 13 were obtained by

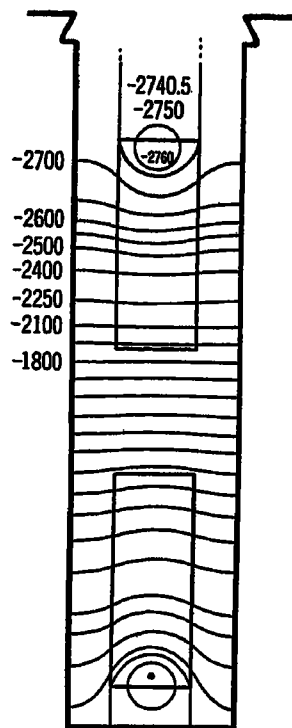


FIG. 14—FIELD ABOUT A TWO-CONDUCTOR SLOT
Currents in the conductors equal but in opposite directions

calculating the flux on the basis that it crosses the slot in straight lines. It makes little difference in the values of total flux above the lower conductor, as indicated by the results.

The case in which the conductors carry equal currents but flowing in the opposite direction is considered next. Whereas both currents in the previous illustration were flowing in a negative direction, that is, up out of the figure, the upper current will now be assumed to flow positively. Within this reversed current district, Region IV, Equation (2) must be altered to read,

$$\frac{\partial^2 R}{\partial x^2} + \frac{\partial^2 R}{\partial y^2} = +4\pi I \quad (17)$$

if I , the current density expressed as a Fourier series, is to be the same as it was before. If, however, I is changed in sign then Equation (2) still will hold. The final regional expression for the upper conductor contains a change of sign before the term including α_n . Such a condition calls for a new determination of all of the coefficients in the regional equations because these relations must be solved simultaneously. The analysis for this case is given in Appendix E.

Fig. 14 illustrates the field about the same two conductors of Fig. 12, the upper current now being reversed. At the bottom of the slot and well up the

sides, the flux plot is practically dependent only on the lower conductor because of the extremely weak field in that region produced by the reversed current above. Within the upper copper, however, the lines rapidly change their shape, eventually closing within the slot about a second kernel.

Fig. 15 shows the field in detail about the second kernel. Immediately about the kernel the flux travels in approximately elliptical paths, the outer approaching the slot walls and closing upon themselves at very great distances. Beyond this group of lines the flux strikes the sides of the slot. These plots verify those determined graphically by Calvert and Harrison.⁴

Flux plots for armature slots of a synchronous machine are necessarily dependent upon instantaneous values of current, except for full-pitch coils. In these instances the currents in the conductors bear a constant relation to each other. The field plot will then have the same conformation although a changing magnitude of total flux. In actual practise full-pitch windings are seldom used, the usual design being somewhere near $\frac{2}{3}$ pitch armature coils. The currents in the upper and lower conductors now differ in time-phase, and for each instant of time there corresponds a new flux plot.

The method by which a field map may be made for any ratio of conductor currents is very simply outlined. The only important step is to adjust the signs of the Fourier series for the current densities of Regions II and IV. For currents in the same direction both series will have the same sign which will depend upon the direction of the current flow. For opposite currents the series will then of course have opposite signs. Substitution of these current density forms in the

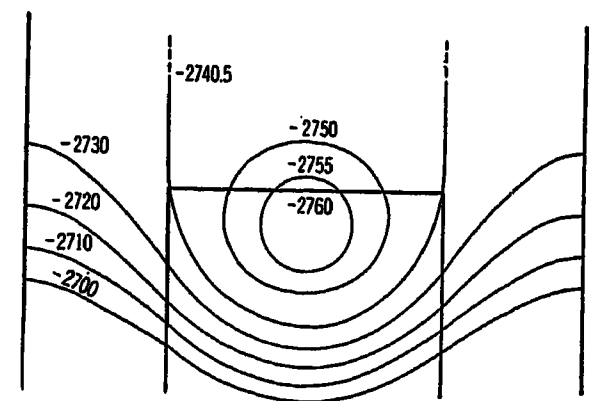


FIG. 15—DETAILED FIELD SHOWING WHIRL OF FLUX ABOUT TOP OF UPPER CONDUCTOR OF FIG. 14

regional equations will automatically care for all algebraic signs which follow.

The regional expressions for R for the cases of two conductors in a slot, one above the other, were obtained by treating the field as a unit. That is, the entire field was divided into five distinct districts, the relations for which were solved simultaneously in order to satisfy the boundary conditions. The resultant R expressions may also be obtained from the equations of the single conductor slot by the principle of superposition. Since

saturation is excluded from the problem, fluxes may be superposed as well as m. m. fs., which was fundamental to the other method.

Fig. 16A shows a slot with only the lower conductor present. The Roman numerals refer to both the regions and their accompanying equations which are those developed in Section II of the paper. Fig. 16B shows only the upper conductor in the slot, the regional expressions for which also are derived in Section II. These last equations are the same as those previously obtained except for a change of slot dimensions. The R equations represent magnetic fields, hence superposition allows of the addition of the sets of regional expressions for the two conductors considered separately. The resulting derivations for the five regions are indicated in Fig. 16C. These two methods have been used in the paper as a check on each other.

VII. INDUCTANCE COMPARISON

One of the most important applications of flux plotting is the determination of the inductance of a current carrying system. To illustrate the method, the inductance of the conductors in the slot under consideration has been determined. In a paper recently pre-

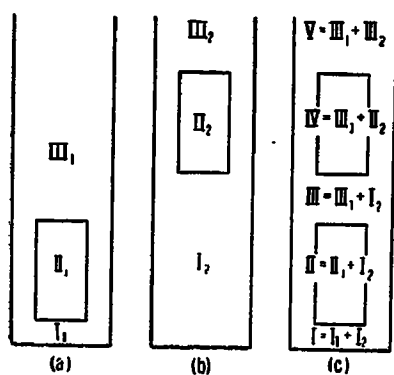


FIG. 16—ADDITION OF REGIONAL EQUATIONS FOR SUPERPOSITION OF FIELDS

sented to the Institute by Mr. P. L. Alger,³ a very complete discussion was presented on the leakage reactance of the armature winding of a synchronous machine. In his paper, slot leakage inductance is calculated by assuming that the flux lines in the slot go straight across. This, of course, involves an error because the curvature of the lines as seen in the plot of Fig. 13 is such that a given flux will link more current than if the flux goes straight across the slot; therefore, the exact method will give a larger reactance. However, the amount of error due to the approximation will be seen to be so small as to be negligible. The reader is referred to Appendix F for the derivations of the inductance formulas.

The following tabulation shows the various components of inductance as determined graphically by mechanical integration of the flux plot, and, analytically, under the assumption that the flux lines go straight across the slot. This analysis has been carried only to the bottom of the wedge, Fig. 12.

Region	Inductance in (abhenrys)/ N^2	
	Present approximations	Mechanical integration of Fig. 13
II	0.150	0.138
III	0.250	0.250
IV	1.005	0.950
V	0.758	0.753
	2.163	2.091

This comparison shows an increase of approximately 3.5 per cent in the inductance determined from the mathematical flux plot. Such an increase is very reasonable since the assumption that the flux lines go straight across the slot is in error to some extent in regions near the bottom of the slot. This is shown in the figure, the values on the outside of the slot indicating the flux determined on this basis.

In Appendix G the inductance of the two conductor slot is determined mathematically from the vector potential R . The expression therein derived shows directly the magnitude of the correction term which gives the increase of inductance due to the curvature of the flux lines above the inductance calculated on the assumption that the lines of flux go straight across the slot. The correction term becomes, by omission of the insignificant terms

$$L' = \frac{l^3}{c^2 a^2 \pi^3} \left(c - \frac{l}{2\pi} \right) \sin^2 \frac{a\pi}{l} \times 10^{-9} \text{ henrys per } N^2 \quad (18)$$

This is simple enough for use in design formula wherever it affects the accuracy to an appreciable extent.

For the slot of Fig. 13

$$L' = 0.087 \times 10^{-9} \text{ henrys per } N^2$$

or an increase over that obtained by Equation (12f) of about 4.1 per cent.

This agrees with the increase in inductance obtained from the flux plot, being slightly higher because the mechanical integration of the flux plot is limited to finite increments whereas the mathematical method deals with infinitesimal increments.

VIII. DETAILED PLOTS

The flux plot of Fig. 17 has been made for general interest to show in detail the field about the kernel of a conductor. The distance between the lower face of the conductor and the slot bottom was made great enough to bring out the whirl of flux in a pronounced manner. The calculations were obtained from Equations (14) and (15) of Section III of the paper, it being assumed that the slot and conductor were infinitely long. Other dimensions are

$$a = 0.45 \text{ in.}, d = 0.90 \text{ in.}, i = 2700 \text{ amperes per sq. in.}$$

The width of the conductor in this particular case was chosen exactly equal to half of the slot width, and it was found that such a ratio of dimensions eliminates all second harmonic functions of the general R equations.

This reduces calculations to some extent. Of further interest is the fact that in Figs. 13 and 17 there is one line which is a continuation of the sides of the conductor below the conductor. Preliminary calculations for the case of $a = 2b$ show this line to be $R = 0$, but this in turn is only true because of the assumption that $A_0 = 0$. The $R = 0$ line of Fig. 17 has been pushed back to the kernel as it was in the former case, so as to give actual values of flux as one proceeds outward from the kernel.

SUMMARY

The usual types of rectangular slots met in practise have been considered, and the general method of attack

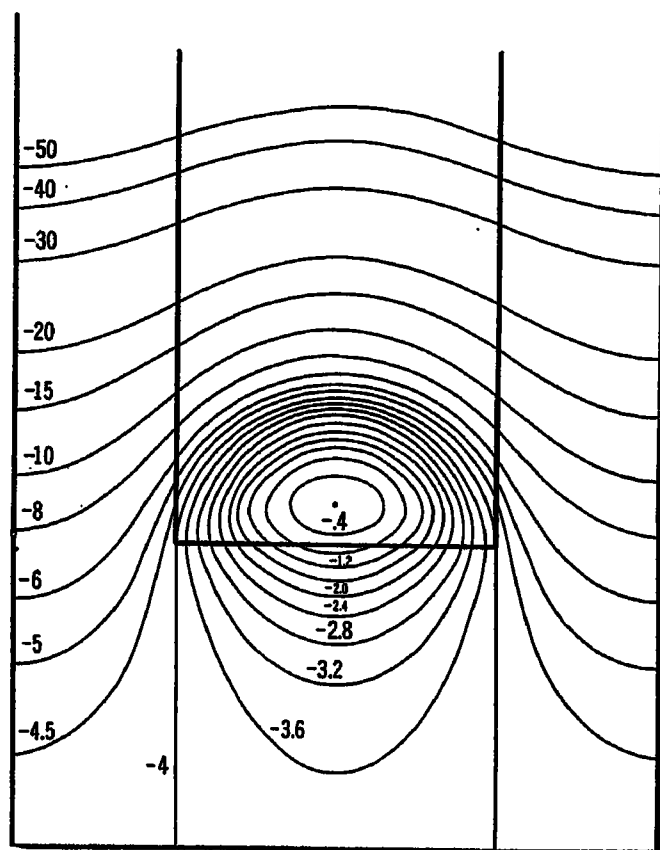


FIG. 17—DETAILED FIELD OF A CONDUCTOR SHOWING WHIRL OF FLUX ABOUT KERNEL

in determining the flux distribution about them has been given in sufficient detail to make its application to other examples quite clear and straightforward. The general equations which have been developed may be applied to any slot by simply substituting for the particular dimensions involved.

The error in inductance calculated on the assumption that the flux tubes go straight across the slot has been shown to be small enough to be negligible in usual slots met in practise, thereby indicating that present assumptions give sufficiently accurate results for engineering purposes.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. L. P. Shildneck for the treatment of Appendix A of the paper, to Dr. E. J. Berg of Union College for his kindness in reviewing the manuscript and offering valuable comments, and to Mr. R. E. Doherty for his helpful suggestions.

Appendix A

PROPERTIES OF THE VECTOR POTENTIAL R

In the second section of the paper, under "fundamental equations," La Place's and Poisson's equations were solved by assuming that a vector potential function R exists such that

$$R = f(x, y) \quad (1a)$$

R is the magnitude of the z component of the vector potential of the magnetizing force and satisfies the relations

$$\frac{\partial R}{\partial x} = -Y$$

$$\frac{\partial R}{\partial y} = X \quad (2a)$$

x and y are the space coordinates and X and Y are the intensities of the magnetic field in the x - and y - directions, respectively. The form of the function was then determined, and with the solutions for R in the various regions, the flux lines were drawn by plotting curves for $R = \text{a constant}$, increments of R being taken as increments of flux. The relation between the vector potential and flux is not an obvious one to persons unfamiliar with vector analysis, and although some of the results of this Appendix have been given before, this short analysis is included for the sake of clarity. This development is due to Mr. L. P. Shildneck, one of the authors' associates.

In order that the curves of $R = \text{a constant}$ shall represent flux lines, it is necessary and sufficient that these curves have: first, the same slope at every point as the flux lines; and second, equal increments of flux enclosed by lines of equal increments of R throughout the entire field.

Lines of $R = \text{a constant}$ may be shown to have the same slope as the flux lines as follows: The components of the field intensity in the x - and y - directions being X and Y , respectively, the slope of the flux lines is Y/X . Since

$$R = f(x, y)$$

the total differential of R is

$$dR = \frac{\partial R}{\partial x} dx + \frac{\partial R}{\partial y} dy \quad (3a)$$

If the equations $R = f(x, y)$ are plotted for $R = \text{a constant}$, then along any curve $dR = 0$, or

$$\frac{\partial R}{\partial x} dx + \frac{\partial R}{\partial y} dy = 0 \quad (4a)$$

whence

$$\left(\frac{dy}{dx} \right)_R = - \frac{\frac{\partial R}{\partial x}}{\frac{\partial R}{\partial y}} = \frac{Y}{X} \quad (5a)$$

Therefore, curves of $R = \text{a constant}$ have the same slope as the lines of force.

The following method can be used to show that

equal increments of R give equal increments of flux throughout the field of force. Fig. 18 shows a section of the field $R = f(x, y)$. Let $V = \phi(x, y) = a$ constant be the equipotential lines, which are orthogonal to the flux lines and therefore to the $R = f(x, y) = a$ constant lines.

Similar to Equation (5a), the slope of the lines $V = a$ constant is

$$\left(\frac{dy}{dx}\right)_V = -\frac{\frac{\partial V}{\partial x}}{\frac{\partial V}{\partial y}} \quad (6a)$$

Since these two systems are orthogonal, the slope of the

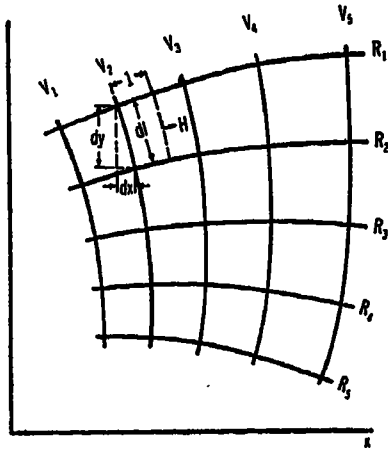


FIG. 18—EQUIPOTENTIAL LINES AND FLUX LINES IN A GENERAL FIELD

R curves must equal the negative reciprocal of the slope of the V curves, or

$$\left(\frac{dy}{dx}\right)_R = -\frac{1}{\left(\frac{dy}{dx}\right)_V} \quad (7a)$$

so that

$$\frac{\frac{\partial R}{\partial x}}{\frac{\partial R}{\partial y}} = -\frac{\frac{\partial V}{\partial y}}{\frac{\partial V}{\partial x}} \quad (8a)$$

At any point, P , in the field, the intensity is given in magnitude by

$$H = (X^2 + Y^2)^{\frac{1}{2}} = \left[\left(\frac{\partial R}{\partial y}\right)^2 + \left(-\frac{\partial R}{\partial x}\right)^2 \right]^{\frac{1}{2}} \quad (9a)$$

and the flux density is

$$\mu H = \mu \left[\left(\frac{\partial R}{\partial y}\right)^2 + \left(-\frac{\partial R}{\partial x}\right)^2 \right]^{\frac{1}{2}} \quad (10a)$$

Considering an elementary area of unit width and of length in the direction of $V = a$ constant

$$dl = [(dx)^2 + (dy)^2]^{\frac{1}{2}}$$

then the flux enclosed between any two lines of force, $R = R_1$ and $R = R_2$, is

$$\phi_{R_2} - \phi_{R_1} = \mu \int_{R=R_1}^{R=R_2} \left[\left(\frac{\partial R}{\partial x}\right)^2 \right]^{\frac{1}{2}} dx$$

$$+ \left(\frac{\partial R}{\partial y}\right)^2 \right]^{\frac{1}{2}} [(dx)^2 + (dy)^2]^{\frac{1}{2}} \quad (11a)$$

Transforming,

$$\begin{aligned} [(dx)^2 + (dy)^2]^{\frac{1}{2}} &= \left[1 + \left(\frac{dy}{dx}\right)^2 \right]^{\frac{1}{2}} dx \\ &= \left[1 + \left(-\frac{\frac{\partial V}{\partial x}}{\frac{\partial V}{\partial y}}\right)^2 \right]^{\frac{1}{2}} dx = \left[1 + \left(\frac{\frac{\partial R}{\partial y}}{\frac{\partial R}{\partial x}}\right)^2 \right]^{\frac{1}{2}} dx \\ &= \left[\left(\frac{\partial R}{\partial x}\right)^2 + \left(\frac{\partial R}{\partial y}\right)^2 \right]^{\frac{1}{2}} \frac{dx}{\frac{\partial R}{\partial x}} \end{aligned} \quad (12a)$$

whence

$$\phi_{R_2} - \phi_{R_1} = \mu \int_{R=R_1}^{R=R_2} \left[\left(\frac{\partial R}{\partial x}\right)^2 + \left(\frac{\partial R}{\partial y}\right)^2 \right]^{\frac{1}{2}} \frac{dx}{\frac{\partial R}{\partial x}} \quad (13a)$$

The first term in the brackets of Equation (13a) becomes directly

$$\left(\frac{\partial R}{\partial x}\right)^2 \frac{dx}{\frac{\partial R}{\partial x}} = \frac{\partial R}{\partial x} dx \quad (14a)$$

From Equation (8a), for any curves $R = a$ constant and $V = a$ constant,

$$dx = -\frac{\frac{\partial V}{\partial y}}{\frac{\partial V}{\partial x}} dy = \frac{\frac{\partial R}{\partial x}}{\frac{\partial R}{\partial y}} dy \quad (15a)$$

The second term in the brackets becomes

$$\left(\frac{\partial R}{\partial y}\right)^2 \frac{dx}{\frac{\partial R}{\partial x}} = \left(\frac{\partial R}{\partial y}\right)^2 \frac{\frac{\partial R}{\partial x} dx}{\frac{\partial R}{\partial y} \frac{\partial R}{\partial x}} dy = \frac{\partial R}{\partial y} dy \quad (16a)$$

Therefore,

$$\phi_{R_2} - \phi_{R_1} = \mu \int_{R=R_1}^{R=R_2} \left[\frac{\partial R}{\partial x} dx + \frac{\partial R}{\partial y} dy \right] \quad (17a)$$

From Equation (17a) it is seen that the expression to be integrated is simply the total differential, dR .

$$\therefore \phi_{R_2} - \phi_{R_1} = \mu \int_{R=R_1}^{R=R_2} dR = \mu (R_2 - R_1) \quad (18a)$$

This means that if equal increments of R are chosen, then the flux between any two adjacent lines of force is the same.

It is interesting to note at this point that if the initial conditions which R must satisfy, Equation (2a), had been chosen such that

$$\frac{dy}{dx} = \frac{\frac{\partial R}{\partial y}}{\frac{\partial R}{\partial x}} = -\frac{X}{Y} \quad (19a)$$

or more explicitly

$$\left. \begin{aligned} \frac{\partial R}{\partial x} &= -X \\ \frac{\partial R}{\partial y} &= Y \end{aligned} \right\} \quad (20a)$$

the function $R = \text{a constant}$ would have given equipotential lines.

Appendix B

APPROXIMATE DETERMINATION OF FLUX

In calculating the flux created by a current-carrying conductor in a slot, and in obtaining the inductance of the slot due to this flux, it is usual practise to make the basic assumption that the lines of force go straight across the slot. Although this procedure gives inaccurate results for certain regions, in general the approximation for the entire field is sufficient for engineering

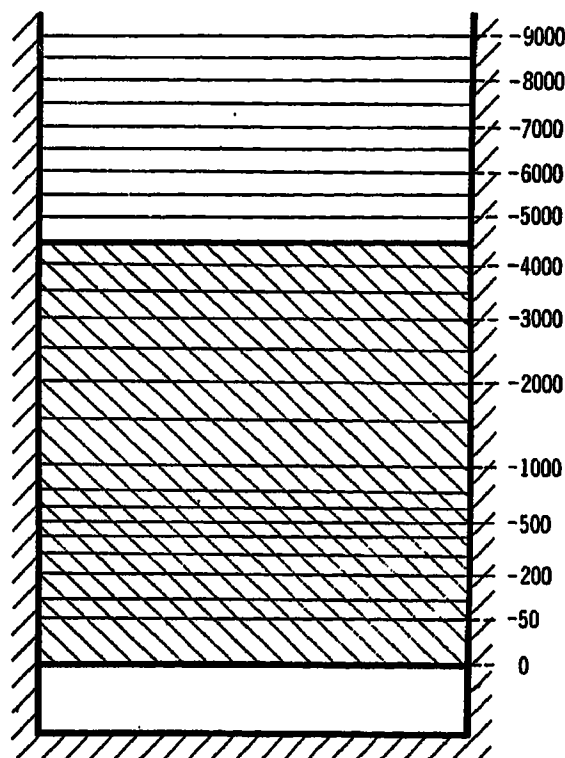


FIG. 19—CONDUCTOR TOUCHING SIDES BUT NOT BOTTOM OF SLOT

answers. To check the values obtained by the more accurate method of Rogowski, the flux has also been calculated by this process, a short discussion of which is here included.

Consider unit length of the slot shown in Fig. 12. The flux through the tube of height dx is

$$d\phi = 4\pi i' \frac{x}{c} \cdot \frac{dx}{w} \quad (1b)$$

where i' is the total current in abamperes of the conductor. The first part of the right member of Equation (1b) is the m. m. f. below the tube considered, and the second part of this member is the permeance of the tube.

Integrating, the total flux included in the interval x is therefore

$$\phi_x = \frac{4\pi i'}{cw} \cdot \frac{x^2}{2} \text{ Maxwells per unit length} \quad (2b)$$

and the total flux within the conductor is

$$\phi = \frac{2\pi i' c}{w} \text{ Maxwells per unit length} \quad (3b)$$

It was from Equation (2b) that the values given to the right of Figs. 6, 7, 8, and 13 were obtained.

From this discussion it is obvious that if the flux lines go straight across the slot, the height of the conductor above the bottom of the slot has no effect on the form of the field. As far as total flux is concerned, Fig. 19, which shows an air space beneath the copper, is identical with Fig. 8. There is no flux between the lower face of the conductor and the slot bottom. This is not true for the general case illustrated in the body of the paper.

Appendix C

CONDUCTOR TOUCHING BOTTOM BUT NOT SIDES OF SLOT

The special case in which the conductor does not touch the sides of the slot, but does come in contact with the bottom, is easily obtained from the general treatment by omitting Region I from that discussion. That is, Regions II and III only of the general case are now present in the new problem.

The Fourier series for the current density is identical in form to that formerly determined since any region below the conductor in no way affects the current density of the region in which the copper is situated.

The general solution of the problem is given by regional Equations (11) and (12) in the main body of the paper.

The constants for those equations are calculated as before by consideration of the boundary conditions between regions, and thus

$$B_0 = 0 \text{ (assumed)}$$

$$B_0' = 0$$

$$B_0'' = -\pi \alpha_0$$

$$B_n = -\frac{2\pi \alpha_n}{n^2 k^2} e^{-nkd}$$

$$B_n' = B_n$$

$$C_0 = \pi \alpha_0 c^2$$

$$C_0' = -2\pi \alpha_0 c$$

$$C_n = 0$$

$$C_n' = \frac{2\pi \alpha_n}{n^2 k^2} (e^{nkd} - e^{-nkd})$$

The final regional equations are

Region II:

$$R = -\pi \alpha_0 x^2 + \sum_{n=1}^{\infty} \left[B_n (e^{nky} + e^{-nky}) + \frac{4\pi \alpha_n}{n^2 k^2} \right] \cos nky \quad (1c)$$

Region III:

$$R = \pi \alpha_0 c^2 - 2 \pi \alpha_0 c x + \sum_{n=1}^{\infty} C_n' \epsilon^{-nkx} \cos n k y \quad (2c)$$

Fig. 7 in the body of the paper was plotted with the

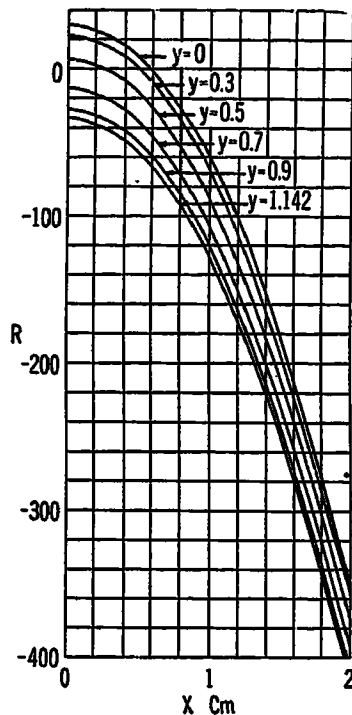


FIG. 20—CURVES OF R AGAINST x , PARAMETER y , FOR CASE SHOWN IN FIG. 7

aid of the auxiliary curves shown in Figs. 20 and 21, the constants for the slot and conductor being

$$\begin{aligned} a &= 0.45 \text{ in.} \\ b &= 0.225 \text{ in.} \\ c &= d = 1.63 \text{ in.} \\ i &= 1960 \text{ amperes per sq. in.} \end{aligned}$$

In this case also, the $R = 0$ line has been pushed back to the kernel by the addition of a certain amount of negative flux. The lines of R shown in Fig. 7 then become the actual quantities of flux produced by the current in the conductor.

Appendix D

SLOT WITH TWO CONDUCTORS CARRYING EQUAL CURRENTS IN THE SAME DIRECTION

The general method of attacking the problem of two conductors in a slot was outlined in Section IV of the paper. This appendix contains the general equations and constants for the above case in which the conductors carry equal currents in opposite directions.

The regional equations for R are similar to those formerly obtained.

Region I:

$$R = A_0 + A_0' x + \sum_{n=1}^{\infty} (A_n \epsilon^{nkx} + A_n' \epsilon^{-nkx}) \cos n k y \quad (1d)$$

Region II:

$$R = B_0 + B_0' x + B_0'' x^2$$

$$+ \sum_{n=1}^{\infty} \left(B_n \epsilon^{nkx} + B_n' \epsilon^{-nkx} + \frac{4 \pi \alpha_n}{n^2 k^2} \right) \cos n k y \quad 2d$$

Region III:

$$R = C_0 + C_0' x + \sum_{n=1}^{\infty} (C_n \epsilon^{nkx} + C_n' \epsilon^{-nkx}) \cos n k y \quad (3d)$$

Region IV:

$$R = D_0 + D_0' x + D_0'' x^2 + \sum_{n=1}^{\infty} \left(D_n \epsilon^{nkx} + D_n' \epsilon^{-nkx} + \frac{4 \pi \alpha_n}{n^2 k^2} \right) \cos n k y \quad (4d)$$

Region V:

$$R = E_0 + E_0' x + \sum_{n=1}^{\infty} (E_n \epsilon^{nkx} + E_n' \epsilon^{-nkx}) \cos n k y$$

The constant terms of the above regional equations are determined, as outlined in Section III, by substituting the boundary conditions and equating coefficients. The boundary conditions are as follows:

a. At the bottom of the slot, coordinate $x = 0$, since the lines must enter the iron at right angles to the surface, $Y = -\partial R / \partial x = 0$

b. At the boundaries between each of the regions the lines of force are continuous (because the permeability is constant) and therefore R and its first partial

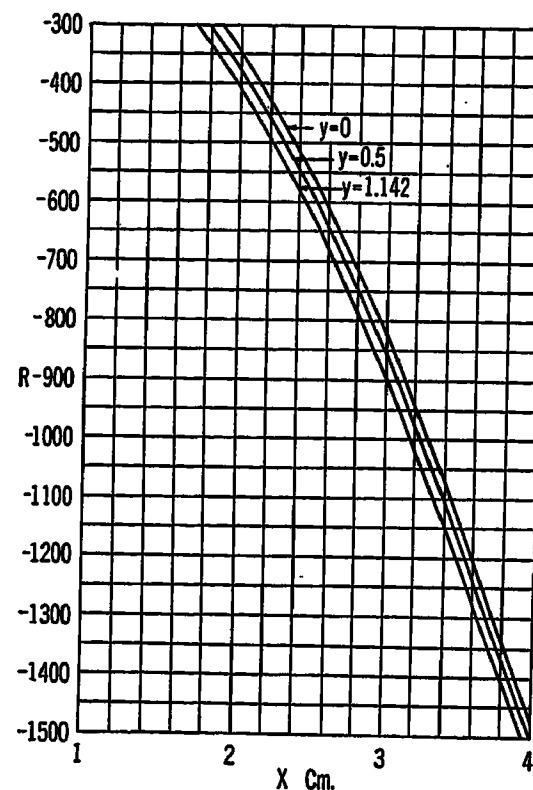


FIG. 21—CURVES OF R AGAINST x , PARAMETER y , FOR CASE SHOWN IN FIG. 7

derivatives with respect to x and y must be continuous.

c. For large values of x the flux goes straight across the slot, so $X = 0$ and $Y = \text{constant}$.

d. The value of the sum of the terms independent of $\cos n k y$ can be obtained from Equation (2b)

There result twenty-one equations for twenty-two unknowns, and by assuming $A_0 = 0$ the constants are obtained as follows:

$$A_0 = 0 \text{ (assumed)}$$

$$A_0' = 0$$

$$A_n = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+e)} + \epsilon^{-nk(d-c)} - \epsilon^{-nkd} - \epsilon^{-nk(d+c+e)}]$$

$$A_n' = A_n$$

$$B_0 = -\pi \alpha_0 (d-c)^2$$

$$B_0' = 2 \pi \alpha_0 (d-c)$$

$$B_0'' = -\pi \alpha_0$$

$$B_n = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+e)} - \epsilon^{-nkd} - \epsilon^{-nk(d+c+e)}]$$

$$B_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} - \epsilon^{-nkd} - \epsilon^{-nk(d+c+e)} + \epsilon^{-nk(d+e)}]$$

$$C_0 = \pi \alpha_0 (2cd - c^2)$$

$$C_0' = -2 \pi \alpha_0 c$$

$$C_n = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+e)} - \epsilon^{-nk(d+c+e)}]$$

$$C_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} - \epsilon^{-nkd} + \epsilon^{nkd} - \epsilon^{-nk(d+c+e)} + \epsilon^{-nk(d+e)}]$$

$$D_0 = \pi \alpha_0 (2cd - 2de - c^2 - d^2 - e^2)$$

$$D_0' = 2 \pi \alpha_0 (d+e-c)$$

$$D_0'' = -\pi \alpha_0$$

$$D_n = \frac{-2 \pi \alpha_n}{n^2 k^2} \epsilon^{-nk(d+c+e)}$$

$$D_n' = \frac{2 \pi \alpha_n}{n^2 k^2} \{ \epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} + \epsilon^{-nk(d+e)} - \epsilon^{nk(d+e)} - \epsilon^{-nkd} + \epsilon^{nkd} - \epsilon^{-nk(d+c+e)} \}$$

$$E_0 = 2 \pi \alpha_0 (2d+e)c$$

$$E_0' = -4 \pi \alpha_0 c$$

$$E_n = 0$$

$$E_n' = \frac{2 \pi \alpha_n}{n^2 k^2} \{ \epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} - \epsilon^{-nkd} + \epsilon^{nkd} + \epsilon^{-nk(d+e)} - \epsilon^{nk(d+e)} - \epsilon^{-nk(d+c+e)} + \epsilon^{nk(d+c+e)} \}$$

The final equations for R in the various regions become very cumbersome when the constants are substituted so they are omitted here.

The dimensions of the slot, Fig. 12 are:

$$a = 0.45 \text{ in.}$$

$$b = 0.225 \text{ in.}$$

$$c = 1.18 \text{ in.}$$

$$d = 1.405 \text{ in.}$$

$$e = 0.715 \text{ in.}$$

$$f = 0.53 \text{ in.}$$

The R -curves from which the above plot was made

are shown in Figs. 22, 23, and 24, for a current of 1036 amperes per conductor.

Appendix E

SLOT WITH TWO CONDUCTORS CARRYING EQUAL CURRENTS IN THE OPPOSITE DIRECTION

Reference was made to this appendix in Section IV of the paper under the discussion of the above case.

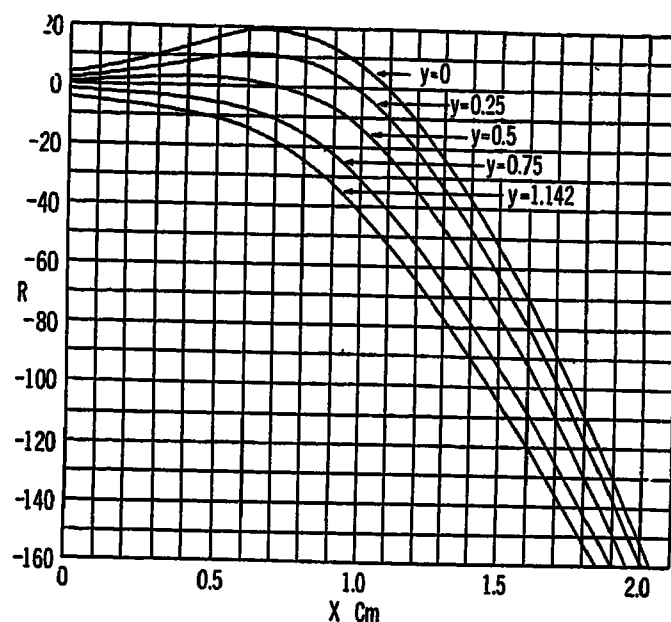


FIG. 22—CURVES OF R AGAINST x , PARAMETER y , FOR CASE SHOWN IN FIG. 13

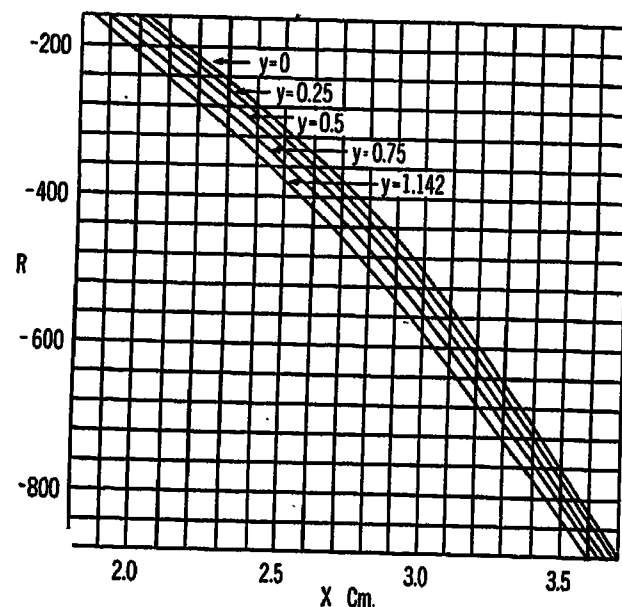


FIG. 23—CURVES OF R AGAINST x , PARAMETER y , FOR CASE SHOWN IN FIG. 13

The regional equations for R are:

Region I:

$$R = A_0 + A_0' x + \sum_{n=1}^{n=\infty} (A_n \epsilon^{n k x} + A_n' \epsilon^{-n k x}) \cos n k y \quad (1e)$$

Region II:

$$R = B_0 + B_0' x + B_0'' x^2 + \sum_{n=1}^{n=\infty} \left(B_n \epsilon^{n k x} + B_n' \epsilon^{-n k x} + \frac{4 \pi \alpha_n}{n^2 k^2} \right) \cos n k y \quad (2e)$$

Region III:

$$R = C_0 + C_0' x + \sum_{n=1}^{\infty} (C_n \epsilon^{nkx} + C_n' \epsilon^{-nkx}) \cos n k y$$

Region IV:

$$R = D_0 + D_0' x + D_0'' x^2$$

$$+ \sum_{n=1}^{\infty} \left(D_n \epsilon^{nkx} + D_n' \epsilon^{-nkx} - \frac{4 \pi \alpha_n}{n^2 k^2} \right) \cos n k y \quad (4e)$$

Region V:

$$R = E_0 + E_0' x + \sum_{n=1}^{\infty} (E_n \epsilon^{nkx} + E_n' \epsilon^{-nkx}) \cos n k y \quad (5e)$$

The constant terms of these regional expressions are determined as those of Appendix D. The boundary

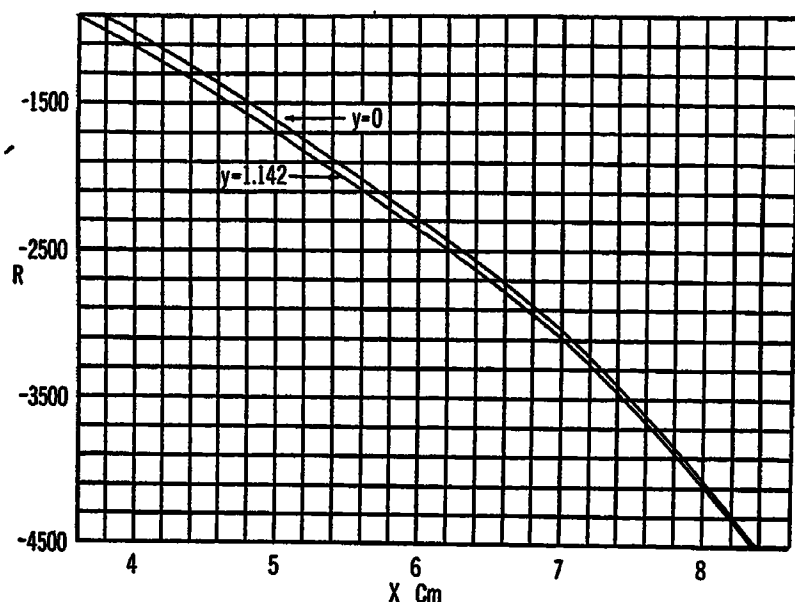


FIG. 24—CURVES OF R AGAINST x , PARAMETER y , FOR CASE SHOWN IN FIG. 13

conditions are the same in the two cases. The constants are as follows:

$$A_0 = 0, \text{ (assumed)}$$

$$A_0' = 0$$

$$A_n = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)} - \epsilon^{-nkd} + \epsilon^{-nk(d-c)}]$$

$$A_n' = A_n$$

$$B_0 = -\pi \alpha_0 (d-c)^2$$

$$B_0' = 2 \pi \alpha_0 (d-c)$$

$$B_0'' = -\pi \alpha_0$$

$$B_n = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)} - \epsilon^{-nkd}]$$

$$B_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)} - \epsilon^{-nkd} + \epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)}]$$

$$C_0 = -\pi \alpha_0 (c^2 - 2cd)$$

$$C_0' = -2 \pi \alpha_0 c$$

$$C_n = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)}]$$

$$(3e) \quad C_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)} - \epsilon^{-nkd} + \epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} + \epsilon^{nkd}]$$

$$D_0 = \pi \alpha_0 [2cd - c^2 + (d+e)^2]$$

$$D_0' = -2 \pi \alpha_0 (c+d+e)$$

$$D_0'' = \pi \alpha_0$$

$$D_n = \frac{2 \pi \alpha_n}{n^2 k^2} \epsilon^{-nk(d+c+e)}$$

$$D_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)} - \epsilon^{-nkd} + \epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} + \epsilon^{nkd} + \epsilon^{nk(d+e)}]$$

$$E_0 = -2 \pi \alpha_0 (c^2 + ce)$$

$$E_0' = 0$$

$$E_n = 0$$

$$E_n' = \frac{2 \pi \alpha_n}{n^2 k^2} [\epsilon^{-nk(d+c+e)} - \epsilon^{-nk(d+e)} - \epsilon^{-nkd} + \epsilon^{-nk(d-c)} - \epsilon^{nk(d-c)} + \epsilon^{nkd} + \epsilon^{nk(d+e)} - \epsilon^{nk(d+c+e)}]$$

The current is 1036 amperes per conductor, as before. The R -curves for the detailed plot of this case,

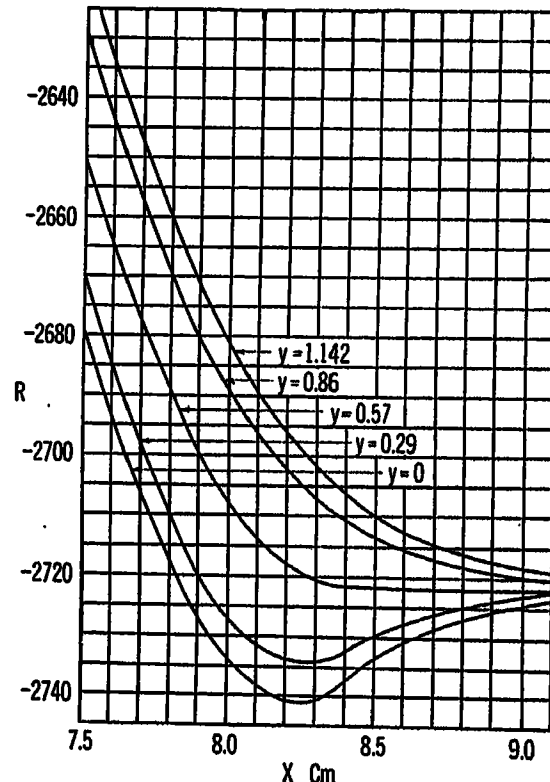


FIG. 25—CURVES OF R AGAINST x , PARAMETER y , FOR CASE SHOWN IN FIG. 15

mentioned in the body of the paper, are given by Fig. 25. From the values of R has been subtracted E_0 .

In calculating R -curves from the above equations, one meets with the terms $\epsilon^{nk(d+c+e)} \epsilon^{-nkx}$. The first exponential involves very large numbers and the second one very small numbers, both of which are not easily obtained on a slide rule or in tables. It is much simpler to reduce all exponential products to a single

term by first adding the exponents. This facilitates calculations because now a slide rule can generally be used.

Appendix F

GRAPHICAL DETERMINATION OF INDUCTANCE

The comparison between the results for the determination of slot inductance, as obtained by graphical methods and as calculated by design formulas, was given in Section VI of the body of the paper. This appendix includes the derivations of the expressions from which these values were obtained.

It will be remembered that the inductance of a system is defined as the flux linkages per ampere. In many problems met in practise, this definition cannot be applied directly, since, as is the case with large conductors, there is a component of inductance due to flux linking only part of the current. It is, therefore, customary to consider a large conductor to consist of a great many smaller conductors connected in series so that all carry the same current. Then the partial linkages become total linkages and the above definition of inductance is applied.

The following additional symbols will be used:

N = the total series turns in a slot (on the basis of the above conception of inductance, N is very large, although practically it need not be).

N' = the series turns linked by any element of flux.

ϕ_n = flux in region n .

A_n = area of copper section in region n .

I = current per turn in amperes.

L_n = inductance in henrys due to flux in region n .

x = distance measured upward from the bottom of the lower conductor.

The inductance of the slot of Fig. 12 will now be determined for each region, Region I, of course, being omitted.

In Region II

$$dL_{II} = \frac{N' d\phi_{II}}{I} 10^{-9} \text{ henrys} \quad (1f)$$

Although Fig. 12 shows the elementary tube of flux going straight across the slot, the tube will in general be curved, see Fig. 13. The interlinkage factor N' in Region II is given by

$$\frac{N}{2} \frac{dA_{II}}{A_{II}}$$

where dA_{II} is the area, or current, enclosed by the element of flux $d\phi_{II}$. $N/2$ is necessary since only half of the total series turns are contained in the lower conductor.

Then the total inductance of this region is

$$L_{II} = \sum \frac{N}{2I} \frac{dA_{II}}{A_{II}} d\phi_{II} 10^{-9} \text{ henrys} \quad (2f)$$

where the summation extends throughout the lower

conductor, and is applied by taking all of the elements dA_{II} enclosed by increments of flux $d\phi_{II}$.

Consider the tube of flux between the - 300 and - 450 lines of Fig. 13. The increment of flux, $d\phi = -150$ lines, surrounds the series turns in the slot given by the ratio of the copper section beneath the - 300 line to the total copper section of the lower conductor. The areas were conveniently determined by a planimeter, this ratio being 0.526. From Equation (2f), that part of the total slot inductance due to the element of flux is,

$$\frac{0.526 \times 150}{1036} \times 10^{-9} = 0.0762 \times 10^{-9} \text{ henrys}$$

based on a slot containing two turns in series. Since inductance is directly proportional to the square of the series turns it would be better to write the above value as 0.019×10^{-9} henrys per N^2 .

The inductance due to any other tube of flux is obtained in an identical manner. The summation of these values throughout the region occupied by the lower conductor will thus give the inductance of the slot due to the current and flux in that region.

It should be mentioned here that the graphical method is accurate only when small increments of flux are taken. For the case at hand, the 150 line intervals are too great and they should be broken up into at least three 50 line periods, which yields a somewhat greater value of inductance than the other calculation.

If the flux lines are assumed to go straight across the slot, then the interlinkage factor becomes

$$\frac{N}{2} \frac{dA_{II}}{A_{II}} = \frac{N}{2} \frac{x}{c}$$

and since the flux through an elementary section of height dx , per centimeter of slot length, is

$$d\phi_{II} = \frac{4\pi NI dx}{w} \text{ Maxwells} \quad (3f)$$

the inductance of Region II is

$$L_{II} = \frac{1}{I} \int_{x=0}^{x=c} \frac{\pi N^2 I}{w} \left(\frac{x}{c} \right)^2 dx 10^{-9} = \frac{\pi N^2 c}{3w} 10^{-9} \text{ henrys} \quad (4f)$$

All of the flux in Region III links all of the current in the lower conductor, hence

$$dL_{III} = \frac{N}{2} \frac{d\phi_{III}}{I} 10^{-9} \text{ henrys}$$

and,

$$L_{III} = \frac{N}{2I} \phi_{III} 10^{-9} \text{ henrys} \quad (5f)$$

to be obtained graphically.

If the flux lines are assumed to go straight across the slot,

$$L_{III} = \frac{\pi N^2 e}{w} 10^{-9} \text{ henrys} \quad (6f)$$

In Region IV the flux links all of the turns in the lower conductor, and in addition $d A_{IV}/A_{IV}$ of the turns in the upper conductor. Thus,

$$L_{IV} = \sum \frac{N}{2I} \left(1 + \frac{d A_{IV}}{A_{IV}} \right) d \phi_{IV} 10^{-9} \text{ henrys} \quad (7f)$$

to be obtained graphically.

Considering the flux to go straight across,

$$\begin{aligned} L_{IV} &= \frac{1}{I} \int_{x=0}^{x=c} \frac{\pi N^2 I}{w} \left(1 + \frac{x}{c} \right)^2 dx 10^{-9} \\ &= \frac{7 \pi N^2 c}{3 w} 10^{-9} \text{ henrys} \end{aligned} \quad (8f)$$

In Region V the flux links all N turns

$$L_V = \frac{N}{I} d \phi_V 10^{-9} \text{ henrys} \quad (9f)$$

graphically, or for the assumption of flux lines straight across the slot,

$$L_V = \frac{4 \pi N^2 f}{w} 10^{-9} \text{ henrys} \quad (10f)$$

Summing up, for graphical determination of the inductance,

$$\begin{aligned} L &= L_{II} + L_{III} + L_{IV} + L_V \\ &= \frac{N}{I} \sum \left[\frac{d A_{II}}{2 A_{II}} d \phi_{II} + \frac{d \phi_{III}}{2} \right. \\ &\quad \left. + \frac{1}{2} \left(1 + \frac{d A_{IV}}{A_{IV}} \right) d \phi_{IV} + d \phi_V \right] 10^{-9} \text{ henrys} \end{aligned} \quad (11f)$$

By the assumption that all the flux lines go straight across,

$$L = \frac{4 \pi N^2}{10^9} \left(\frac{8c + 12f + 3e}{12w} \right) \text{ henrys} \quad (12f)$$

This equation is identical, except for nomenclature, with that obtained by Mr. P. L. Alger.³

Appendix G

DETERMINATION OF INDUCTANCE FROM THE VECTOR POTENTIAL R

In Appendix F the inductance of the slot of Fig. 13 was calculated in two ways, one on the assumption that the flux lines go straight across the slot and the other by integrating the flux linkages according to the flux plot, by means of a planimeter. The difference in the inductances as determined by the two different methods is not large in the case under consideration. Since, however, usual design formulas for determining slot inductance are based upon the assumption that the flux lines go straight across the slot, it is of interest

to obtain an expression for the error involved in this assumption.

Messrs. Stevenson and Park included in an appendix to their paper a discussion on the calculation of inductance from a knowledge of the vector potential. The method there used of attacking the problem is so fundamentally clear that it will be followed in this analysis. The total inductance of the slot up to the bottom of the wedge will be determined. It will be found to consist of the inductance determined on the usual assumptions, and an additional term which is due to the curvature of the flux lines. By neglecting the unimportant components of this additional term it reduces to the simple correction term given in the body of the paper.

Let ϕ be the total flux from the bottom of the lower conductor up to the bottom of the wedge. Then outside of any line R the flux will be,

$$\phi + R_0 - R$$

where R_0 is the value of the vector potential at the bottom of the lower conductor. The linkages at the line R , considering the lower and upper conductor to have the same turns, are

$$N' (\phi + R_0 - R) = (\phi + R_0 - R) \frac{N d A}{2 A}$$

where A is the total area of the copper in the slot and $d A = dx dy$ is the area of copper inside of the line R . The inductance is then,

$$L = \frac{N}{2I} \int_s (\phi + R_0 - R) \frac{d A}{A} \quad (1g)$$

where the integral $\int_s$ is to extend over both of the copper areas.

Since $I = A i$,

$$L = \frac{N}{2I^2} \int_s (\phi + R_0 - R) i d A \quad (2g)$$

$\phi + R_0$ is independent of the element $d A$ and $\int_s i d A = 2 I$ so,

$$\frac{N}{2I^2} \int_s (\phi + R_0) i d A = \frac{N}{I} (\phi + R_0) \quad (3g)$$

or,

$$L = \frac{N}{I} (\phi + R_0) - \frac{N}{2I^2} \int_s R i d A \quad (4g)$$

$R_0 + \phi$ can be obtained by substituting in the vector potential equation for Region V the values of $x = c + d + e + f$ and $y = 0$.

$$R_v = E_0 + E_0' x + \sum \dots \dots \dots$$

$$\phi + R_0 = - \frac{2 \pi a i c}{l} \left\{ 4 c + 2 e + 4 f \right\} + \sum (5g)$$

The first term of the above inductance for a two turn coil is,

$$\frac{N}{I} (\phi + R_0) = - \frac{4 \pi}{l} \left\{ 4 c + 2 e + 4 f \right\} \quad (6g)$$

The negative sign need cause no alarm as it simply indicates the direction of the induced voltage.

The second term of the inductance formula (4g) requires the surface integral of R over the two current carrying regions.

For Region II, considering a two turn coil

$$- \frac{1}{I^2} \int_s R_{II} i dA = - \frac{i}{I^2} \int_{y=-a/2}^{y=a/2} \int_{x=d-c}^{x=d} \left\{ B_0 + B_0' x + B_0'' x^2 + \sum (B_n e^{nkx} + B_n' e^{-nkx} + \frac{4 \pi \alpha_n}{n^2 k^2}) \cos n k y \right\} dx dy \quad (7g)$$

$$= \frac{2 \pi c}{3 l} - \sum \frac{2 i}{I^2} \sin n k a/2 \left\{ \frac{B_n}{n^2 k^2} [\epsilon^{nkd} - \epsilon^{nk(d-c)}] - \frac{B_n'}{n^2 k^2} [\epsilon^{-nkd} - \epsilon^{-nk(d-c)}] + \frac{4 \pi \alpha_n c}{n^3 k^3} \right\} \quad (8g)$$

For Region IV,

$$- \frac{1}{I^2} \int_s R_{IV} i dA = - \frac{i}{I^2} \int_{y=-a/2}^{y=a/2} \int_{x=d+e}^{x=c+d+e} \left\{ D_0 + D_0' x + D_0'' x^2 + \sum (D_n e^{nkx} + D_n' e^{-nkx} + \frac{4 \pi \alpha_n}{n^2 k^2}) \cos n k y \right\} dx dy \quad (9g)$$

$$= \frac{2 \pi}{l} \left(\frac{7}{3} c + 2 e \right) - \sum \frac{2 i}{I^2} \sin a n \pi / l \left\{ \frac{D_n}{n^2 k^2} [\epsilon^{nk(c+d+e)} - \epsilon^{nk(d+e)}] - \frac{D_n'}{n^2 k^2} [\epsilon^{-nk(c+d+e)} - \epsilon^{-nk(d+e)}] + \frac{4 \pi \alpha_n c}{n^3 k^3} \right\} \quad (10g)$$

Representing the two summations by $\sum$ for compactness

$$L = - \frac{4 \pi}{l} \left\{ \frac{8 c + 3 e + 12 f}{12} \right\} - \sum (11g)$$

Excluding $\sum$ the inductance is the same as that

developed assuming the flux lines go straight across the slot. $\sum$ must then be the correction term due to their curvature.

By substituting in the constants B_n , B_n' , D_n , and D_n' and neglecting all terms which are insignificant in slots encountered in actual practise the correction term becomes

$$L' = \sum \frac{-l^3}{c^2 a^2 \pi^3 n^4} \left(c - \frac{l}{2 n \pi} \right) \sin^2 \frac{a n \pi}{l} \quad (12g)$$

which is to be added for $\sum$ in Equation (11g).

NOMENCLATURE

a, b, c, d, e, f , and l	= slot and conductor dimensions, see Fig. 12.
$A_n, A_n', B_n, B_n' \dots$ etc.	= constants of the Fourier series of the regional equations.
H	= magnetic field intensity.
i	= conductor current density in abamperes per square centimeter.
i'	= total conductor current in abamperes.
I	= current density in general. In Appendix E, used as current per turn.
k	= $2 \pi / l$.
l	= $a + 2 b$, also used as w , the slot width.
L	= inductance in abhenrys.
L'	= inductance correction factor.
n	= an integer, 1, 2, 3, . . . etc.
R	= vector potential of the magnetic field.
R_n	= function of integration dependent upon x alone, and coefficients of the Fourier series for R . In Appendix A, R_n is used to designate lines of force.
V	= vector potential of a field orthogonal to that of R .
w	= slot width in Appendixes B and F.
x	= distance measured upward from bottom of lower conductor.
x, y	= general coordinates.
X	= x -component of H .
Y	= y -component of H .
α_n	= coefficient of the n th term of the Fourier series for the m. m. f. distribution.
β_n, γ_n	= coefficients of the solutions for R_n .
ϕ	= flux in total lines.
μ	= permeability, ∞ for iron, unity for air, insulation, and copper.

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Discussion

K. A. Reeve: Although the authors of the paper *Analytical Determination of Magnetic Fields* are concerned mostly with the practical case of two conductors in a slot, one above the other, as is typical of synchronous-machine design, I should like to point out that the method of approach which they use in solving the problem can be applied to the general case of slot design for d-c. machines in which there may be four, six, eight or more coil sides in a slot, each coil side being considered a conductor.

As an illustration of this application, consider the simple case of four conductors placed two horizontally and vertically in a slot. Let the conductors in the bottom row carry equal currents, and those in the top row also carry equal currents, but not of the same magnitude or direction of the current as in the lower row. This case may be solved by considering the Fourier series, as done in the paper, and then applying the correction factor, as given by Maxwell in Volume I, paragraph 693, of his "Electricity and Magnetism," to care for the space between the conductors. It may also be solved by changing the Fourier series for the current density, such that the curve will have two rectangular loops. The substitution of this series in Poisson's equation is all that is then required.

It is also possible by this method to solve the case in which the currents in all conductors are not the same, and the case in which conductors are staggered vertically but not horizontally. Although the last condition is not realized in practise, it nevertheless shows the generality of the authors' treatment.

A. D. Moore: This contribution breaks down one more of the barriers to the understanding of typical field cases. Many of the barriers are insurmountable. Every time a new set of problems in magnetic fields is solved, our ability to handle unsolved problems is improved. Knowledge of the general character of a field, and of its main tendencies, is far better than an uninformed guess. Hence, although the practical slot violates to some degree every assumption underlying solutions reached in the paper, yet these solutions will usually apply with satisfying accuracy. And when one must estimate (*estimate* being here a refined synonym for *guess*) fields which nobody ever will be able to solve, the accuracy of the estimate is likely to bear a close relation to one's knowledge of correct solutions of ideal cases.

If the paper does no more than to cause college textbooks of the future to differ from those of the past by presenting generally correct rather than generally ridiculous representations for slot fields, the labor spent in preparing it will have been amply justified.

J. J. Smith: (communicated after adjournment) The authors have obtained very interesting solutions for the flux distribution about rectangular conductors in rectangular slots. It is evident that considerable skill and ingenuity were required in the determination of the various constants of integration given for instance in Equation (13).

It may be of interest to point out that a more symmetrical form of solution may be written down from which the various results may be obtained by simple integrations. This can be obtained by letting the thickness of the conductor in a radial direction in the slot approach zero (i. e., $c \rightarrow 0$). We have then only two regions (I) and (III) to deal with. The expressions for vector potential become (expanding e^{nkc} in a series and neglecting c^2 and higher powers of c)

Region I—

$$R = \sum_{n=1}^{\infty} L t \frac{2 \pi \alpha_n}{n^2 k^2} e^{-nkd} \left[e^{nkc} - 1 \right] \left[e^{nkx} + e^{-nkx} \right] \cos nky$$

$$= \sum_{n=1}^{\infty} L t \frac{2 \pi \alpha_n c}{n k} e^{-nkd} \left[e^{nkx} + e^{-nkx} \right] \cos nky \quad (1)$$

Region III—

$$R = L t 2 \pi \alpha_o c (d - x)$$

$$+ \sum_{n=1}^{\infty} L t \frac{2 \pi \alpha_n}{n^2 k^2} \left[e^{-nkd} (e^{nkc} - 1) + e^{nkd} (1 - e^{-nkc}) \right] e^{-nkx} \cos nky$$

$$= L t 2 \pi \alpha_o c (d - x)$$

$$+ \sum_{n=1}^{\infty} L t \frac{2 \pi \alpha_n c}{n k} e^{-nkd} \left[e^{nkd} + e^{-nkd} \right] \cos nky \quad (2)$$

It will be noted in this form that (except for $n = 0$) the various terms in region III are obtained from the terms in region I by interchanging x and d . The solution can be made completely symmetrical by adding $L t \pi \alpha_o c (x - d)$ to the expression for each region—this is legitimate since the authors' solution is based upon an arbitrary assumption that $A_o = 0$. We then obtain for region I

$$R = L t \pi \alpha_o c (x - d)$$

$$+ \sum_{n=1}^{\infty} L t \frac{2 \pi \alpha_n c}{n k} e^{-nkd} \left[e^{nkx} + e^{-nkx} \right] \cos nky \quad (3)$$

and if we write

$$\alpha_o = \alpha_o' i \text{ and } \alpha_n = \alpha_n' i \quad (4)$$

and also write $L t i c a = I$ where I is the total current in the conductor, then for region I

$$R = \frac{\pi \alpha_o' I (x - d)}{a} + \sum_{n=1}^{\infty} \frac{4 \pi \alpha_n' I}{n k a} e^{-nkd} \cosh nkx \cos nky \quad (5)$$

and the expression for region III is obtained by interchanging x and d .

I have checked this solution with the result obtained for a more general problem which is as follows: The vector potential due to a filament of current I placed at the point (x_1, y_1) in an infinitely deep slot the equations of whose sides are given by $x = 0, y = 0$ and $y = l$ is

$$v = L t I \cos \frac{p \pi y}{l} \cos \frac{p \pi y_1}{l} A_p$$

$$+ 2 I \sum_{p=1}^{\infty} \cos \frac{p \pi y}{l} \cos \frac{p \pi y_1}{l} A_p$$

where

$$A_p = \frac{4}{p} \cosh \frac{p \pi x}{l} e^{-\frac{p \pi x_1}{l}} \quad (x < x_1)$$

$$= \frac{4}{p} \cosh \frac{p \pi x_1}{l} e^{-\frac{p \pi x}{l}} \quad (x > x_1) \quad (6)$$

My interest in this solution for a current filament lies chiefly in the fact that it may be derived by means of an extension of the Heaviside Operational Calculus which makes the derivation of such results almost an automatic procedure. I hope to illustrate how such results can be obtained in an Institute paper sometime in the near future.

If the total current in the infinitely thin strip of width a is I , the current in the element dy_1 is $I dy_1/a$. Hence changing

the origin from $y = 0$ to $y = l/2$ (to conform with Messrs. Robertson and Terry's notation) and integrating from $-a/2$ to $+a/2$ we get for the vector potential

$$\begin{aligned}
 v = R &= \frac{I}{a} \int_{-a/2}^{+a/2} L t \cos \left[\frac{p \pi}{l} \left(y + \frac{l}{2} \right) \right] \cos \left[\frac{p \pi}{l} \left(y_1 + \frac{l}{2} \right) \right] A_p dy_1 \\
 &+ \frac{2I}{a} \int_{-a/2}^{+a/2} \sum_{p=1}^{\infty} \cos \left[\frac{p \pi}{l} \left(y + \frac{l}{2} \right) \right] \cos \left[\frac{p \pi}{l} \left(y_1 + \frac{l}{2} \right) \right] A_p dy_1 \\
 &= \frac{I}{a} L t \frac{A_p \cos \left[\frac{p \pi}{l} \left(y + \frac{l}{2} \right) \right]}{\frac{p \pi}{l}} \left[\sin \left[\frac{p \pi}{l} \left(\frac{l}{2} + \frac{a}{2} \right) \right] \right. \\
 &\quad \left. - \sin \left[\frac{p \pi}{l} \left(\frac{l}{2} - \frac{a}{2} \right) \right] \right] \\
 &+ \frac{2I}{a} \sum_{p=1}^{\infty} \frac{A_p \cos \left[\frac{p \pi}{l} \left(y + \frac{l}{2} \right) \right]}{\frac{p \pi}{l}} \left[\sin \left[\frac{p \pi}{l} \left(\frac{l}{2} + \frac{a}{2} \right) \right] \right. \\
 &\quad \left. - \sin \left[\frac{p \pi}{l} \left(\frac{l}{2} - \frac{a}{2} \right) \right] \right] \\
 &= L t \frac{2 l I A_p \cos \left[\frac{p \pi}{l} \left(y + \frac{l}{2} \right) \right] \cos \frac{p \pi}{2} \sin \frac{p \pi a}{2 l}}{p \pi a} \\
 &+ \frac{4 I}{a} \sum_{p=1}^{\infty} \frac{A_p l \cos \frac{p \pi y}{l} \cos^2 \frac{p \pi}{2} \sin \frac{p \pi a}{2 l}}{p \pi} \quad (7)
 \end{aligned}$$

Now $\cos^2 \frac{p \pi}{2} = 0$ when p is odd, and $= 1$ when p is even.

Hence writing $p = 2n$ we obtain

$$\begin{aligned}
 R &= L t I A_n + \frac{4 I l}{a} \sum_{n=1}^{\infty} \frac{A_{2n} \cos \frac{2 \pi n y}{l} \sin \frac{n \pi a}{l}}{2 n \pi} \\
 &= L t I A_n + \sum_{n=1}^{\infty} \frac{4 I l}{2 n \pi a} \cos \frac{2 n \pi y}{l} \sin \frac{n \pi y}{l} \frac{4}{2 n} \\
 &\quad \cosh \frac{2 n \pi x}{l} e^{-\frac{2 n \pi x_1}{l}} \quad (x < x_1) \\
 &= L t I A_n \\
 &\quad + I \sum_{n=1}^{\infty} l \frac{4}{n k l} \sin \frac{n k a}{2} \cos n k y \frac{4}{2 n a} \cosh n k x e^{-n k x_1} \quad (x < x_1) \\
 &= L t I A_n + I \sum_{n=1}^{\infty} \alpha_n' \cos n k y \frac{4 \pi}{n k a} e^{-n k x_1} \cosh n k x \quad (x < x_1) \quad (8)
 \end{aligned}$$

If d is now written instead of x_1 this expression, except for the first term ($n = 0$) is identical with the value derived for R in (5) from the results obtained in Messrs. Robertson and Terry's paper.

The term for $n = 0$ is infinite on account of the presence of

the factor n in the denominator of A_n . This infinite term is due to the fact that the vector potential has been assumed to be zero at infinity in deriving the expression for a current filament. It is easy to show, however, that the difference between the terms for $n \rightarrow 0$, for $x > x_1$ and for $x < x_1$ is the same as that derived from the authors' paper in (5). We have for this difference

$$\begin{aligned}
 L t \frac{4 I}{p} \left[\cosh \frac{p \pi x}{l} e^{-\frac{p \pi x_1}{l}} - \cosh \frac{p \pi x_1}{l} e^{-\frac{p \pi x}{l}} \right] \\
 = L t \frac{4 I}{p} \left[1 - \frac{p \pi x_1}{l} - 1 + \frac{p \pi x}{l} \right] \\
 = \frac{4 I \pi}{l} (x - x_1) = \frac{2 I \alpha_o' \pi (x - x_1)}{a} \quad (9)
 \end{aligned}$$

and writing d for x_1 this is equal to the difference between the first terms already obtained for regions I and III in (5).

It may be well to note here that although the results obtained in Messrs. Robertson and Terry's paper can be obtained from the vector potential for a current filament, the reverse process is not possible. This is due to the fact that they have assumed symmetry for the current about the axis $y = 0$. I would suggest that they briefly indicate how their solution could be extended to a current distribution which was not symmetrical about that axis. Of course, such a problem is not as important as the ones considered in the paper since in practical cases we have such symmetry.

We have thus obtained a check from another source on the authors' work, which resulted in satisfactory agreement. In connection with the special cases discussed in Section V of the paper it may be worth while to point out that any rectangular

strip filling the slot from side to side (from $y = -\frac{l}{2}$ to $y = \frac{l}{2}$)

and extending from $x = c$ to $x = d$, gives flux lines which go straight across the slot and gives no flux below the conductor. The various plots given by them are very interesting in actually showing that the error is small in the ordinary assumption that the flux goes across the slot in straight lines, and thus the calculation of self-inductance under this assumption is sufficiently close for practical purposes.

B. L. Robertson: We wish to thank Professor Moore for his comments on the paper. Professor Moore has been quite interested in the subject of flux plotting over a considerable number of years, perhaps more from the graphical than the analytical standpoint, and this work has been of further interest to him as a verification of free-hand field mapping.

The paper was prepared from the practical point of view as much as possible, and we are glad that Mr. Reeve has shown the application of the general method to additional fields. The d-c. machine, since its design is usually of more than two coil sides per slot, is the problem Mr. Reeve has in mind. As he says, there are different ways of obtaining the solution, but the simpler one is that in which the Fourier series for the current density is changed. The number of rectangular loops in the current density plot will then be equal to the number of conductor (coil side) widths in a slot. In general, it will be necessary to obtain a new current density curve, and its accompanying Fourier series, for each row of conductors. Current density curves for each row also takes care of the cases in which the conductors might be staggered vertically but not horizontally.

I. A. Terry: The authors also wish to thank Mr. J. J. Smith for presenting an alternative method of solving the cases considered in the paper. The completely symmetrical form of the equations obtained by considering conductor filaments has a number of advantages over the form given in the paper, not the least important of which is the fact that the derivation of the

results becomes almost automatic by using Operational Calculus.

A complete treatment of this subject by means of Operational Calculus should prove to be of great value to persons interested in analytical determination of magnetic or other orthogonal systems.

In regard to the extension of the solution to the case of a current distribution not symmetrical about the $y = 0$ axis, it will be remembered that the method of solution used in the paper requires the current density curve to be expressible in the form of a Fourier Series. (See Fig. 3 of the paper.) So long as this condition is fulfilled the solution is obtained as in the paper.

For example, if a slot contains two conductors in the same

horizontal plane carrying unequal currents, then the current density curve will be similar to Fig. 3 except that every alternate group of two loops will be of the same height and determined by the current in each conductor, as can be seen from the application of the method of images. The fundamental period will now cover two slots (one slot and either adjacent image) instead of one slot alone.

In the case of some slots used in d-c. machines, as mentioned by Mr. K. A. Reeve, the current density has the form which Mr. Smith has considered not so important as those in the paper. The authors feel that these cases are equally as important but limited the present paper to simple cases of conductors in slots.

Shielding and Guarding Electrical Apparatus Used in Measurements—General Principles

BY HARVEY L. CURTIS*

Fellow, A. I. E. E.

Synopsis.—*Electrical measuring apparatus is shielded and guarded to protect it from the following external influences; namely, leakage currents, electrostatic fields, magnetic fields, and electromagnetic waves. Apparatus is guarded against leakage currents which may flow over or through the solid insulators on which the apparatus is supported. It is shielded against leakage currents which flow through the fluid in which the instrument is immersed. By a proper arrangement of guards and shields any apparatus can be completely protected against leakage currents.*

Any apparatus can be completely shielded from electrostatic fields by placing it in a metallic case. However, there may be electrostatic reactions between the apparatus and the shield, thus introducing errors in the measuring apparatus.

Shielding apparatus from magnetic fields requires that the apparatus be surrounded by a thick enclosure of magnetic material. The theory of this magnetic shielding has been developed and formulas for producing the most satisfactory shielding are given.

The shielding of an apparatus from electromagnetic waves is largely accomplished by means of eddy currents which these waves set up in the shield. The theory for the production of these eddy currents has been developed and the best location of shields is discussed.

Some attention is given to the errors which may be introduced by shielding and some methods are outlined for obviating the necessity of shielding.

* * * * *

I. INTRODUCTION

GUARDS and shields are used with electrical measuring apparatus either to simplify its theory or to protect it from external influences. The simplification of theory has generally resulted from a rearrangement of the electric or magnetic field so that the resulting field can be more easily subjected to mathematical analysis. The external influences from which apparatus must be protected are: (1) Leakage currents, (2) magnetic fields, (3) electrostatic fields, (4) electromagnetic waves.

It is the purpose of this paper to discuss the general principles underlying the guarding and shielding of electrical apparatus.

The protection of apparatus from external influences has sometimes been called guarding the apparatus and sometimes shielding it. The following definitions seem to represent the best practise: A shield protects apparatus from those outside influences which may penetrate to the instrument through the medium by which it is surrounded. A device for the protection of apparatus from leakage currents which, for the most part, flow over the surfaces of the solid insulators used to support the apparatus is called a guard. The term "guard" is also applied to those devices the purpose of which is to rearrange the electric or magnetic field. For example, the earthed plates which are sometimes put under the insulating supports of an electrometer to prevent leakage currents are called guard plates, while if the electrometer is surrounded by a metal covering to protect it from the ionization currents of the air, this covering is a shield. Also, if a parallel

plate condenser has one plate surrounded by a ring to diminish edge effects, this ring is a guard ring. However, if the back of the guarded plate is surrounded by a housing to prevent any electrostatic lines from reaching the back of the plate, this housing is a shield. While these usages of the terms "shield" and "guard" might, to advantage, be modified, they will be adhered to throughout the paper.

Guards and shields have been largely developed in connection with apparatus for measuring some electric phenomenon. The present paper will consider this use only. However, the general principles that apply to the guarding and shielding of measuring apparatus can often be applied to such different problems as reducing the danger to life in high-voltage systems and protection from lightning.

II. GUARDING AND SHIELDING APPARATUS AGAINST LEAKAGE CURRENTS

Guarding apparatus against leakage currents is necessary whenever the solids used in the insulation of the apparatus have so low a volume resistance or surface resistance as to allow a leakage current to flow which will influence the measuring apparatus. Shielding apparatus against leakage currents is necessary whenever the fluid (air, oil, etc.) in which the apparatus is immersed permits a measurable current to flow. In ordinary measurements, guarding against leakage is required more often than shielding.

The leakage currents against which apparatus must be guarded may flow through the material of which the solid insulators are made or through a film of moisture or dirt on the surface of the insulators. With some insulating materials (amber, ceresin, hard-rubber, paraffin, silica-glass, sulphur, etc.), the leakage current through the material of the insulator is negligibly small in well designed apparatus. Surface leakage, on the other hand, is often troublesome, especially since it may be quite variable. The method of guarding, how-

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ever, is the same for both volume and surface leakage.

To guard an apparatus as completely as possible every insulator is made in two parts. One part of each insulator supports a piece of metal (the guard) on which is mounted the second part that in turn supports the measuring apparatus. An auxiliary electric circuit, similar to the one in the measuring apparatus, is then set up and so connected to the guards that the potential of each guard is substantially the same as that of the conductor in the measuring apparatus which it supports. Hence there is no tendency for a leakage current to flow through or over the second part of the insulator which is between the measuring apparatus and the guard.

In practise no apparatus can be completely guarded. There is very sure to be some potential difference between the different guards and the measuring apparatus. No amount of guarding will take the place of good insulation. However, in some cases where it is

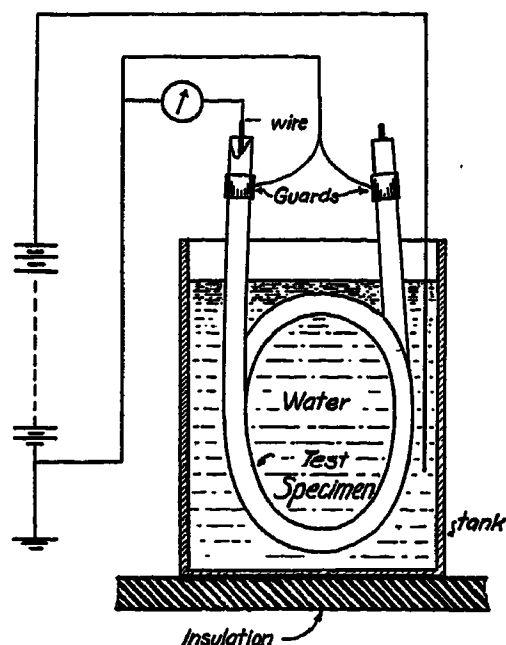


FIG. 1—DIAGRAM TO SHOW METHOD OF USING GUARDS IN THE MEASUREMENT OF THE INSULATION RESISTANCE OF A WIRE OR CABLE

impractical to make the insulation resistance very high, excellent results can be obtained by guarding. One example is the well known Price guard wire² that is regularly used in measuring the insulation resistance¹ of wires and cables. The principle of this is illustrated in Fig. 1.*

Without the guards, the leakage current over the surface of the insulation between the wire and the water may be even greater than the current through the insulation, thus making valueless any determination of the insulation resistance of the cable. With the guards at the same potential as the wire, this leakage current does not reach the wire, and hence does not produce a deflection of the galvanometer. However, it is often difficult to maintain the guard at the same potential as

the wire. This may be caused by the measuring current producing a drop in potential across the resistance of the galvanometer, or by electrolytic action at the guard or wire. When there is a potential difference between the guard and wire, this will cause a flow of current through the galvanometer. This will be negligible only if the insulation resistance between the wire and guard is sufficiently high.

It is sometimes desirable to employ a guard to prevent leakage currents from lighting and power circuits from reaching a measuring circuit. Where it is feasible, this guarding can be accomplished by mounting the entire measuring circuit, including the source of e. m. f., on grounded metal plates. Where such a procedure is not feasible, portions of a circuit which are difficult to insulate may, to advantage, be guarded. For example, in Fig. 1, the galvanometer may be guarded by mounting it on a grounded metal plate. Also, if the conductor which connects the galvanometer to the wire of the cable is supported on solid insulators, each of these may well be mounted on a grounded guard plate. However, there is little advantage in guarding the insulators that support the conductor which connects the battery to the water surrounding the cable.

Shielding air-immersed apparatus against leakage currents is necessary only when the apparatus is sensitive to exceedingly small currents or when the number of ions is unusually large. No general statement can be made as to the sensitivity of apparatus that requires shielding. It is customary and usually necessary to shield the essential portions of a circuit when an electrometer³ is employed as the measuring instrument. It is usually unnecessary to shield when using a galvanometer unless the instrument is exceedingly sensitive or the surrounding air highly ionized.

III. GUARDING APPARATUS TO SIMPLIFY ITS THEORY

In some types of measurements, it is desirable to determine the constants of the apparatus from the known properties of the surrounding medium. In such cases a guard may be employed either to confine the field of the measuring apparatus to that portion of space where the properties are known, or to modify the field so that the constants of the apparatus can be computed from its dimensions. In many cases one guard may perform both of these functions. A well known example is a guard-ring air condenser. Here the guard ring is useful not only to confine the lines of force to the air so that the dielectric loss is negligible, but also to make the field between the plates uniform so that the capacitance can be readily computed.

While guards are often useful, they should be used with care lest they introduce errors which are greater than those they are supposed to rectify. The possibility of errors is well illustrated by the guard-ring condenser. When it is used as a standard having zero power factor in a-c. measurements, the assumption is

1, 2. For references see Bibliography.

*Here the current which flows over the surface of the insulation is, by means of the guards, shunted around the measuring instrument.

tacitly made that the potential of the guard ring is at *every instant* the same as the potential of the guarded plate. This requires not only that the two alternating potentials shall have the same magnitude and be in the same phase, but also that they shall have the same wave form. Hence, not only must the impedance of the guard circuit be properly adjusted, but also it must be protected from corona and other effects which would change its wave form. Again, when the guard ring is used to simplify the computation of the capacitance, the edge correction is not zero unless the gap between the guard and plate is infinitely narrow. Hence, a correction⁴ must, for precise work, be applied to the computed capacitance to allow for the finite width of the gap.

IV. SHIELDING OF A SPACE FROM ELECTROSTATIC FIELDS

A given space can be perfectly shielded from external electrostatic fields by surrounding the space with a continuous metallic enclosure which is maintained at a definite potential, usually at earth potential. Provided this could always be used, nothing further would have to be written concerning electrostatic shields. The shield, however, may react unfavorably on the apparatus that is being shielded. In such cases it may be necessary or advisable to omit the shield entirely, or to use less effective methods of shielding.

The most troublesome reaction between apparatus and shield is caused by capacitance. The placing of a grounded shield close to a piece of apparatus will very markedly increase not only the capacitance to earth but also the capacitance between parts of the shielded apparatus. As an example consider a shielded resistance coil. Often such a shield is used to make definite the capacitance between the different parts of the coil, particularly that between the terminals. However, if the shield is placed very close to the terminals, slight changes in the position of the shield (such as those produced by changes in temperature) may cause changes in the capacitance between the terminals greater than the changes which would have occurred had no shield been present. This difficulty can readily be overcome by making the shield larger.

When it is not feasible to use metallic sheets in constructing a shield, woven wire netting or a grating of parallel wires may be found satisfactory. In such a case the shield should be larger than when using plates since the external electrostatic field may penetrate for short distances inside the netting or grating. The effectiveness will depend upon the size of the wires and upon the spacing between them. Maxwell^{5a} has discussed the theory of the grating but the effectiveness of a netting can only be determined by experiment.

When any form of metallic shield is objectionable, some shielding can be accomplished by enclosing the space with a housing of material which has a high dielectric constant.⁵ While the theory of this method

of shielding is well developed, it is seldom used in experimental work.

V. SHIELDING OF A SPACE FROM MAGNETIC FIELDS

A given space can be shielded from a constant magnetic field only by surrounding the space by magnetic materials. Perfect shielding is not possible but good results can be obtained by the use of suitable materials provided they are in the most efficient shapes.

The shielding of spaces against the earth's magnetic field is probably the oldest problem in magnetic shielding. It early became of importance in the design and use of needle type galvanometers. Here the shielding might not be important if the earth's field were perfectly constant. However, the changes are of such long period that the effect of these changes can be made negligible only by reducing the entire field to a very small part of its original value.

The early attempts at magnetic shielding consisted in enclosing the space in a single shell of iron.⁶ Later it was shown that two or more shells could be used to advantage. This problem was first treated theoretically by Rücker⁷ for two and for three spherical shells. Later DuBois⁸ gave a more complete treatment for two spheres and for two cylinders. Wills⁹ extended this to cover three spheres and three cylinders. More recently Esmarch¹¹ and Dye¹⁴ have given the general expression for the shielding produced by any number of cylinders provided their successive radii form a geometric progression.*

All of these derivations have assumed that the external field is uniform and of such a small value that the permeability of the shields can be considered constant. Also the shields are assumed to be concentric and the axes of the cylindrical shields are assumed to be perpendicular to the lines of magnetic force. The cylindrical shields are assumed to be sufficiently long so that end effects can be neglected. In practise this means that the length should be twice the diameter.

The important results of the theoretical investigations can be stated as follows:

1. The shielding ratio (defined as the ratio of the external to the internal magnetic field) is approximately

*Assume there are n shields of permeability μ , the successive radii (starting from the smallest) are $r_1, r_2, \dots, r_{2n}$. The odd subscripts give the inside radii and the even subscripts the outside radii. The shielding ratio, g , ($= H_e/H_i$ where H_e is the external field and H_i is the field inside the shield) is given by the formula

$$g = K_n r_1^2 / r_{2n}^2$$

where $K_n = \{ 2\beta + [\beta - 1]^2 \mu / 4 \} K_{n-1} - \beta^2 K_{n-2}$
in which

$$\beta = \frac{r_2^2}{r_1^2} = \frac{r_3^2}{r_2^2} \dots = \left(\frac{r_{2n}^2}{r_1^2} \right)^{\frac{1}{2n-1}}$$

Since K_n depends on K_{n-1} and K_{n-2} , the values for K_1 and K_2 are not given by this formula. They are

$$K_1 = 1 + (\beta - 1) \mu / 4$$

$$K_2 = \{ 2\beta + [\beta - 1]^2 \mu / 4 \} K_1 - \beta$$

Dye¹⁴ gives curves to aid in computing the shielding ratio.

proportional to the permeability of the material of which the shields are constructed.⁸

2. The thickness of the shields should not be great. For example, a single spherical shield, the thickness of which is greater than $\sqrt{2r_1^2/\mu}$, (r_1 = internal radius of shield and μ is permeability), will be improved by removing a spherical lamina, and thus reducing the total amount of shielding material.⁷

3. For both spheres⁷ and cylinders⁹ the best thickness and spacing is that in which the radii of the successive bounding surfaces of the shells are in geometric progression. From this it follows that any increase in the volume of the space to be shielded requires the same relative increase in the volume of the shields.

The experimental verification of the best thickness of shells was undertaken by Nichols and Williams.¹⁰ They constructed three cylindrical shields of silicon steel in which the successive radii had approximately the same ratio. The shielding ratio was measured for various combinations of these shields and also for a set of five shields which were selected at random from available materials. The results are given in Table I.

TABLE I
CYLINDRICAL SHIELDS OF NICHOLS AND WILLIAMS

Shields	Weight kilos	Inner radius cm.	Shielding ratio H_e/H_i
A. Set of three from cast silicon steel. Radii in geometric progression.		2.55	
Inner only.....	1.9		20
Inner intermediate.....	7.5		300
All three.....	26.9		4000
B. Set of five from soft iron water pipes.....		2.65	
Inner only.....	1.5		20
Inner + 1 intermediate.....	3.1		100
Inner + 2 intermediate.....	4.3		250
Inner + 3 intermediate.....	7.2		700
All five.....	9.3		2700

While the method which Nichols and Williams used in determining the shielding ratio has been questioned,¹² the results undoubtedly have some relative significance. The advantages gained from the use of specially prepared shields is relatively small.

Within a few years some experimental work has been done to determine the shielding effect of spirals made from high permeability material. In some cases the shield was made by winding in a tight spiral a single sheet of magnetic material. In other cases, a sheet of magnetic material and a sheet of non-magnetic material (copper or paper) were placed together and wound

into a spiral so that in the resulting shield the magnetic material was interleaved with non-magnetic material. Characteristic results are given in Table II. These results show the value of inter-leaving, though the exact thickness of the inter-leaving does not seem to be important.¹³ The increased shielding that can be obtained by the use of the high permeability alloys of nickel and iron is well illustrated by the values of Hill¹⁵ for mumetal.

The above discussion has dealt only with shielding from constant magnetic fields, yet the same principles apply to the shielding from alternating magnetic fields provided the shielding material is so laminated that the effect of eddy currents in the shields is negligibly small. Under this condition the magnetic field can at any instant be considered as a quasi-stationary state; *i. e.*, it is unnecessary to consider the rate of propagation of the field. However, this is not the case when eddy currents are present in appreciable amounts, for which case the discussion of magnetic shielding coincides with the following section on the shielding from magnetic waves.

VI. SHIELDING A SPACE FROM ELECTROMAGNETIC WAVES

The problem of shielding a space from electromagnetic waves depends on the frequency of these waves. When the frequency is very low, the electric and magnetic fields change so slowly that the shielding problems are nearly identical with those for stationary fields. When the frequency is very high, shielding becomes a problem in the optical opacity of materials. For intermediate frequencies, consideration must be given not only to the instantaneous values of the electromagnetic and electrostatic fields, but also to the rate at which these fields are changing.

Since the shielding from stationary fields has already been considered, this discussion will be confined to principles which are applicable to a changing magnetic and electrostatic field; that is, to electric waves. The frequency range from 10 to 10⁸ cycles per sec. will be considered. In this range, the wavelengths vary from 3×10^7 to 3 meters. Hence the linear dimensions of the region to be shielded are generally small relative to the wavelength.

The shielding from electromagnetic waves is brought about by eddy currents which the waves produce in the shield. These eddy currents radiate waves into space surrounding the shield. Some of these waves may

TABLE II
SHIELDING RATIO OF DIFFERENT MATERIALS

Reference	Kind of magnetic material	Thickness—cm.		Weight kilos	Inner diam. cm.	Outer diam. cm.	Shielding ratio H_e/H_i
		Magnetic material	Interleaves				
13	Transformer steel	0.26	0.14	0.5	4.	8.	180
		0.26	0.		4.	8.	50
		4.	..		4.	8.	20
15	Mumetal	0.15	0.25		10.	12.	10,000

impinge on the apparatus which is producing the waves. This may alter the current in the sending apparatus and thus affect the waves that are being sent out. This interaction between sending apparatus and shield is decreased as the distance between them is increased. Hence, most theoretical investigations have assumed that this distance is so large that the reaction on the sending apparatus can be neglected. Since in any particular case the waves emanate from a single electric circuit, the electric and magnetic vectors at a given place have a definite direction. In the nomenclature of optics, the waves are polarized. The three vectors which determine (1) the direction of motion of the wave, (2) the direction of the electric field, and (3) the direction of the magnetic field are mutually perpendicular. Hence, they may be taken as the axes of a rectangular coordinate system. The effect of a shield will depend on its orientation relative to this coordinate system.

The shielding power of a conductor or system of conductors which is used to protect any given region from waves having a definite direction and wave front is usually defined as the ratio of the decrease in the amplitude of the wave when the shield is present to the original amplitude of the wave at the midpoint of the region.*

Expressed in symbols $S = (A_0 - A_s)/A_0$ where S is the shielding power, A_0 the amplitude of the wave when no shield is present, and A_s the amplitude when the shield is present. If shields are so arranged that in a given space no outside electromagnetic waves can enter, then throughout that space the shielding is 100 per cent, or perfect.

The eddy currents which are set up in the shield may be produced either by the electric field of the wave or by the magnetic field, or by both.¹⁷ The method by which waves produce eddy currents can be made clear by considering some particular cases. First, consider that observations are being made at a point due south of and at considerable distance from a station which is sending out waves from a flat top antenna. Then at the observation station the wave can be considered as a plane wave in which the electric field is vertical, and the magnetic field horizontal in an east and west direction. If a series of vertical wires are erected in an east and west plane, the electrostatic field of the waves will produce eddy currents in the wires, which to some extent will shield the space to the south of the wires. If the wire system is turned through 90 deg. around a north and south axis, then no eddy currents will be produced in the wires by either the electrostatic or magnetic fields and hence no shielding. If the parallel wires are joined in pairs so that they form a series of long, narrow loops, eddy currents will be produced in the loops when they are so placed that the magnetic

field of the wave threads through these loops. This requires that the perpendicular to the plane of the wires shall lie in the direction of the magnetic vector of the wave. Then the eddy currents set up in the loops produce a magnetic field which is opposed to that of the wave. This then produces a shielding beyond the wires.¹⁷

As another example of shielding, consider the shielding power of a cube of metal which may or may not be laminated. Assume a wave like that in the preceding paragraph where the direction of the wave is south, the electrostatic vector vertical, and the magnetic vector horizontal and in the east and west direction. The metal cube rests on a horizontal plane with its faces in the directions of the cardinal points. If the cube is solid metal, eddy currents will be produced by both the electric and magnetic vectors so that points just beyond the south face of the cube will be very well shielded. If now the cube is laminated by means of planes parallel to the east and west faces, the eddy currents will not be affected and the shielding is the same as with a solid cube. Next assume that the laminations are produced by planes parallel to the north and south faces. In this case the electric vector would produce eddy currents as in both the previous cases, but the magnetic vector would not. Hence, the shielding would be reduced. If now the laminations are produced by horizontal planes, the eddy currents from both the electric and magnetic vectors are greatly reduced. Such a block would produce very little shielding.

In order to compute the shielding which will be produced by any arrangement of solid metallic bodies, it is necessary first to compute the eddy currents that will be produced in the metal. The formula for determining the current density in a particular case is generally determined by the solution of Maxwell's differential equations of an electromagnetic field. It results that the eddy currents in a massive conductor are

always a function of $\sqrt{\frac{f\mu}{\sigma}}$, where f is the frequency

of the wave, μ the permeability of the material, and σ its resistivity. This shows that the most effective shielding materials are those having high permeability and low resistivity.

Formulas for computing the eddy currents produced by electric waves have been derived in certain cases.¹⁶ However, in relatively few cases have the theoretical deductions been carried to a point where the shielding power can be computed. Some experimental work¹⁸ has shown that there is a qualitative agreement between theory and experiment.

VII. LIMITATIONS OF SHIELDING

In a previous section, the effect on any measuring apparatus of an electrostatic shield in which it is enclosed was discussed. In any given case, the reaction

*Note that this is different from the definition of shielding ratio. For example, a shielding power of 100 per cent indicates perfect shielding, while the shielding ratio must be infinity to indicate perfect shielding.

between the shielded apparatus and an electrostatic shield can be expressed in terms of the coefficients of capacitance. Likewise a magnetic shield or a shield which protects against electromagnetic waves reacts with the apparatus which it is shielding. However, in neither of the latter cases can the amount of reaction be expressed by a simple formula.

It has already been pointed out that an electrostatic shield may introduce errors in a measuring apparatus for which it is difficult to make a correction. With a magnetic shield, on the other hand, the effect of the reactions is to change the sensitivity of the apparatus. As the apparatus is calibrated with the shield in place, no error results from the use of the shield. However, the reactions are so complicated, involving eddy currents, hysteresis, permeability, etc., that each separate type must be subjected to an experimental investigation.

In absolute electrical measurements, where the constants of an apparatus are computed from the mechanical dimensions, shields must generally be avoided. As an example, the inductance of a coil can often be accurately computed from its dimensions. However, the formula for making the computation is developed on the assumption that the permeability of the surrounding space is unity; that is, that there are no magnetic bodies in the surrounding region. Evidently a magnetic shield would vitiate this fundamental assumption. Moreover, the derivation of the formula takes no account of the capacitance between the parts of the inductance. While this generally produces a negligible effect, yet the presence of an electrostatic shield will so increase the capacitance between parts that an appreciable effect is produced. Hence, an electrostatic shield must be avoided.

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Astatic instruments are often used for obviating the necessity of shielding. In an astatic piece of apparatus two similar parts are constructed. In the finished apparatus these parts are rigidly connected mechanically, but the electric and magnetic circuits are so arranged that an external electric or magnetic field will produce equal and opposite effects in the two parts. When the apparatus is placed in an electric or magnetic field which is uniform throughout the region which the apparatus occupies, then changes in the magnitude of this field will not affect the indications of the instrument. This method has been applied to galvanometers and inductors.

Sometimes shielding can be avoided by counteracting the parasitic field by a field which can be controlled. As an example, it is often desirable to have a region in which the magnetic field is much less than the ever present magnetic field of the earth. If the required region is small this can be accomplished by surrounding the region by a rather large coil of wire, the axis of which lies in the direction of the earth's

field, and sending through the coil a current of such magnitude and direction that the earth's field is neutralized at the center of the coil. If a larger region is required, a solenoid can be used, the axis of which lies in the direction of the earth's field. This has the disadvantage that the region is surrounded by the solenoid so that apparatus placed in this region is not readily accessible. To obviate this difficulty, Helmholtz coils can be used. They are a pair of circular coils having identical dimensions and mounted coaxially. The distance between the planes of the coils is equal to the radius of one of them. When the same current flows through both of these coils so that the magnetic field of both of the coils is in the same direction, then there is a rather large region between the coils where the magnetic field is very nearly uniform. Hence, if the axis of the coils is in the direction of the earth's field, a fairly large region between the coils can, by adjusting the current, be made to have approximately zero field.

The above method of neutralizing the earth's field is satisfactory only when this field is very constant and when the current through the coils does not fluctuate. If the current through the coils could be made to vary at the same time and by the same amount as the earth's field varies, then the compensation could be made perfect at all times. The author suggests the following method for accomplishing this variation in current. Mount a series of copper disks on an insulating shaft which can be driven at constant speed by some non-magnetic motor, such as an air turbine. By placing one brush near the center and another at the circumference, each disk becomes a Faraday wheel generating an e. m. f. proportional to the component of the magnetic field in the direction of the axis of rotation. Connect these in series with each other and with a pair of Helmholtz coils having their axes parallel to the axis of the generator. By a proper adjustment of the size and number of the disks and of the resistance in the circuit, the compensation should be perfect provided that at every instant the earth's field is the same at the generator and at the coils. To compensate for two components of the earth's field, two generators are required and two sets of Helmholtz coils, the latter being mounted concentrically. For three components, three generators and three concentric sets of Helmholtz coils are required.

IX. CONCLUSION

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I am citing the various shades of meaning attached to the word "shielding," because I feel that some of the practical aspects of the question are worthy of note. That great benefits can accrue from applied shielding has been clearly illustrated by the case of Type H Cable. Undoubtedly similar benefits may be obtained in other fields.

The one problem to which I would direct attention is that of ignition wire. Shielding applied to such cables may be used in three senses. First, it may protect against influences inwards, that is, against the interaction between conductors. Second, it may protect against the harmful effects of ozone which is generated incidental to normal operation. Third, it may serve as protection of outside equipment such as radio, etc., from the electromagnetic radiation from the circuit. The advantages to be gained by shielding ignition wire would seem to be of sufficient importance to warrant careful attention.

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would seem to be need for a standard which is comprehensive, one that includes a condenser and that which is necessary to measure the condenser.

Such apparatus it seems to me must be shielded, or guarded, or both, if such a thing is possible,—and I think it is possible. If you don't shield or guard you depend upon a high degree of skill in the user, and probably upon a great deal of available space in which you set up the apparatus, and a great deal of time to make the measurements. If you have a completely shielded and guarded set-up you can probably make out with considerably less technique, less space, and less time. Where dielectric-loss measurements are being used in purchase specifications, it would seem necessary to have definite standards, transfer standards, if you choose, that can be sent to a central bureau such as the Bureau of Standards, for certification and shipped back to the laboratories where they are to be used as secondary standards. Then in individual laboratories the user can make his own choice as to whether he is going to use a shielded equipment or a non-shielded equipment for his routine work, or special investigation. It seems essential to have a shielded and guarded equipment for such transfer between laboratories. This subject involves the Bureau of Standards, and I should like to ask Dr. Curtis in closing his remarks to say a word as to whether for standardizing work and transferring between laboratories, he does not feel that the measuring apparatus must be shielded and guarded.

C. L. Dawes: It is very gratifying to learn that through Dr. Kouwenhoven's investigations the high-voltage air condenser is to be placed on a definite quantitative basis. Many of us have been somewhat apprehensive at times due to the unknown effects of humidity and the losses which it may cause. In order to make certain that losses in our air condenser did not occur in humid weather when our laboratory was not heated, we have applied heat from resistor units placed near the condenser. We are looking forward with interest to the publication of Dr. Kouwenhoven's investigations.

I am in accord with Mr. Stein that we should have more and better dielectric standards. I recall that in the late eighties it was necessary to calibrate d-c. ammeters by weighing the electro-

lytic deposition of copper. It required nearly an hour to calibrate each point. At the moment it seems that we are just a little beyond this stage in the matter of dielectric standards. In time, however, these standards will undoubtedly reach the status of our present electric-circuit standards.

H. L. Curtis: The question of definition which Mr. Peterson has brought up, is one of the most trying and difficult things we have to deal with. We all have to speak the same language and therefore we ought to have definite ideas when we use various terms. However, language is a matter of growth and things come to have definite meanings because we use them in different ways. It is worth while occasionally to stop and see whether we all are speaking the same language, and it was with that in view that I tried to bring out these definitions.

The question of using shielded and guarded apparatus that Mr. Stein has brought up, when transferring standard apparatus from laboratory to laboratory is, without doubt, very important. We have been trying to get the Leeds & Northrup Company for some years to mark their condensers as to whether they were shielded, and if so the shielded side, so they would be perfectly definite in handling and dealing with them from laboratory to laboratory. That is not always done now.

The interest of the people at this convention apparently has been very much toward high-voltage measurements where conditions are difficult and arrangements are very special. Many circuits that have been developed apply particularly to conditions that are developed there.

I wish, however, to call attention to the fact that there are cases where shielding and grounding positively cannot be used. One particular case I have to deal with is the question of a coil the inductance of which can be computed from its dimensions. We base our fundamental electrical units in certain cases on such apparatus, and one requirement for the computing of the inductance is that there shall be no conductor close to the coil.

I have perhaps throughout my paper emphasized rather the difficulties in connection with shielding because of the fact that so often these are overlooked and people use shields and guards with the feeling that no difficulties exist.

Some Problems in Dielectric-Loss Measurements

BY C. L. DAWES*

Member, A. I. E. E.

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and

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Associate, A. I. E. E.

Synopsis.—The measurement of dielectric loss in high-voltage cables presents many problems that are not obvious until such measurements have actually been attempted and the results checked and analyzed. Some of these problems are not simple, and their solution is obtained only after considerable effort and research. This paper presents some of the problems that the authors have encountered in this type of work, together with the methods used for their solution.

The bridge method, which is used for the measurement of dielectric loss, is described in some detail. Details of the auxiliary equipment, such as galvanometer, amplifiers, air condenser, shielding, and special methods of bringing the shielding to the proper potential are also given.

If accurate results are to be had in dielectric loss measurements, the entire bridge, including cable, air condenser, and leads, must be properly shielded and the capacitance between leads and shielding should be made small. Errors of large magnitude may be introduced in the results if these precautions are not taken. It is entirely insufficient to shield the bridge and ground the shielding directly. At times shielding cables may increase the measured losses.

In measuring the capacitance of the air condenser, all stray capacitance to its guard rings and to surroundings must be eliminated. The paper gives a method of accomplishing this.

The voltage across the voltmeter coil of a high-voltage transformer

is frequently taken as a measure of the voltage across its secondary. In some methods of measurement this voltmeter-coil circuit is an integral part of the measuring circuits; consequently, it is desirable to be able to determine accurately the ratio of this voltmeter-coil voltage to the total voltage, and the phase difference existing between these two voltages. Methods of making such measurements are described and considerable quantitative data are given for typical testing transformers under various conditions of load.

Methods of determining the accuracy of the bridge are described, and observed results given. With one type of measurement, the ratio and the current accuracy may be checked simultaneously.

The accuracy of the bridge as a power-measuring device may be determined by inserting known resistances into its arms and comparing computed results with observed results. Due to unsuspected leakage and stray-capacitance currents, however, the introduction of such resistances may cause large errors. Methods for minimizing such currents, as well as analyses of proper and improper methods of making such measurements, are given. Some of the effects of harmonics are described briefly. In this type of measurement they probably do not introduce error, but at times they are troublesome in that they produce anomalous effects in the measuring apparatus.

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INTRODUCTION

DURING the past few years the authors have devoted considerable time to the development of methods for measuring dielectric losses at high voltages. Particularly during the past four years, numerous problems have been encountered during the progress of the research in ionization in impregnated paper-insulated cables being carried on at Harvard University under the auspices of the Joint Committee on Paper-Insulated Cables of the N. E. L. A., A. I. E. E., and A. E. I. Co. The authors believe that as a result of this type of research, which has been stimulated by cable users and manufacturers, engineers have advanced, by many years, the science of measuring very small power at extremely high voltage and very low power factor,—a most difficult combination. However, since factors which ordinarily need not even be considered may introduce large errors, one must always be on guard in making such measurements.

Many of these factors are well known to those who have made a study of the problem. On the other hand, in discussing some of these problems with cable engi-

neers, the authors have been requested to present them in the form of a paper, in order that others might perhaps be forewarned of the many pitfalls into which some have already stumbled. Moreover, it is hoped that the discussion may bring out experiences of others, from which all may derive benefit.

There is probably no type of measurement in which one may be more easily deceived than these dielectric-loss measurements. The losses vary with temperature, with the time of electrification, the cycle of electrification, and with the handling of the specimen. Hence, accurate checks of measurements on cable samples among different laboratories cannot be expected, and it is thus difficult to prove that a measurement is in error. Under the circumstances, it is remarkable that results check as closely as in many instances they were found to do. Curves obtained with certain measuring apparatus may appear perfectly rational, and yet because of phase-angle defect or wrong transformation ratio, both of which may be constant in magnitude, the curves are actually in error. It is most difficult to check a given apparatus by the introduction of known losses in the circuits, as will be shown later. The calibrated Leyden jars, which are now available at the Electrical Testing Laboratories, have in large measure overcome some of these difficulties.

THE BRIDGE METHOD

The authors use the mutual inductance bridge, which has already been described by them.¹ The complete bridge with its shielding and guard connections, as now used, is shown in Fig. 1.

1. For references see Bibliography.

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The simplified bridge circuit is shown in Fig. 2; one arm of the bridge proper consists of the air condenser C_1 and the series resistance R_1 ; the other consists of the cable (or other dielectric) C_2 in series with the primary of a mutual inductance M and the series resistance R_2 . The secondary of the mutual inductance is connected from the point b at one terminal of R_2 to one terminal of the detector D ; the other terminal of D is connected to point a at one terminal of R_1 . When the bridge is in balance, the angle of defect of the cable, $\psi = \tan^{-1} \frac{M \omega}{R_2}$, where M is the mutual inductance in henrys and

$\omega = 2 \pi f$ where f is the frequency in cycles per second. This assumes that the air condenser has no losses.

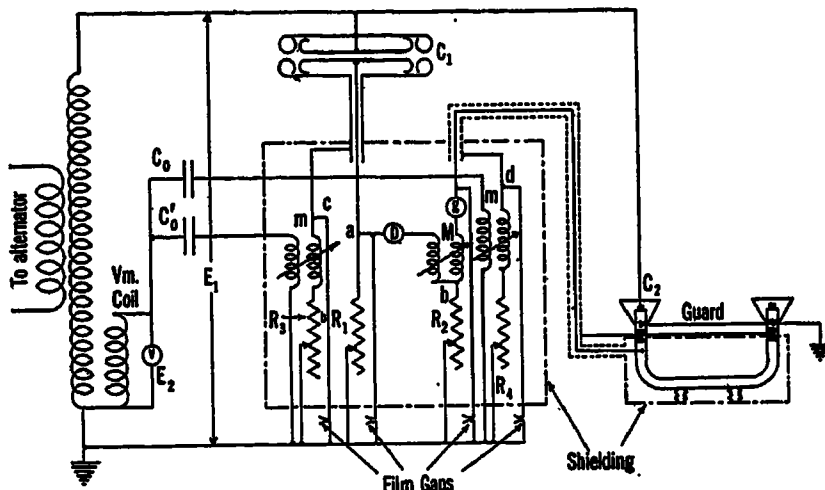


FIG. 1—COMPLETE CONNECTIONS OF BRIDGE CIRCUIT

With low values of power factor,

$$\cos \theta = \sin \psi = \frac{M \omega}{R_2} \quad (1)$$

where θ is the power-factor angle and ψ is the angle of defect of the dielectric. The capacitance C_2 , for low values of power factor, is given by

$$C_2 = C_1 \frac{R_1}{R_2} \quad (2)$$

$$\text{The power} = \frac{E^2 C_2 \omega^2 M}{R_2} = \frac{E^2 C_1 R_1 \omega^2 M}{R_2^2} \quad (3)$$

In checking the bridge by various methods, several errors which were not at first understood appeared and some were run to earth only after long and painstaking investigations, a number of which will be considered later.

THE DETECTOR

Without a sensitive detector, the bridge loses most of its advantages as a precision instrument. For power frequencies from 20 to 125 cycles per second which we use for cable investigations, we have found the tuned iron-vane vibration galvanometer the most satisfactory type of detector. Electromagnetic excitation is employed and the tuning is accomplished by varying the exciting current. An advantage of this type of de-

tector is the fact that the detecting coil may be wound for a wide range of impedance. Hence, the impedance may be made to correspond to the character of the circuit with which it is associated. Since bridges for measuring dielectric losses must necessarily have high-impedance arms, the coil of our galvanometer is wound with No. 40 silk-covered wire. Its impedance is $2200 + j 280$ ohms at 60 cycles.

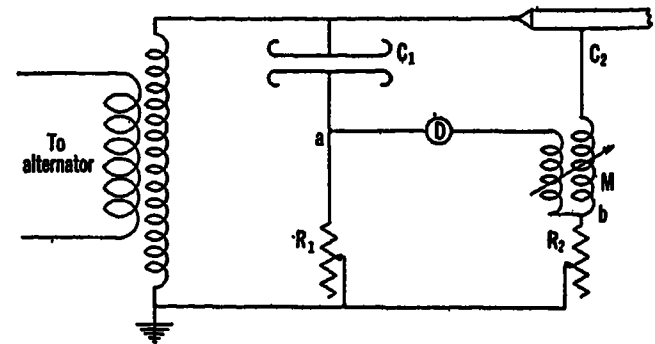


FIG. 2—SIMPLIFIED CONNECTIONS OF BRIDGE CIRCUIT

Another advantage of this type of detector is the fact that the deflection is readily maintained on the scale, even with considerable unbalance, by merely detuning slightly. As the condition of balance is approached, closer tuning is easily obtained.

The degree of sensitivity is tremendously increased by the use of an amplifier in conjunction with the detector. One of the authors has already published a description of the amplifier which they have developed.² There are many refinements in connection with its use, however, which might be useful to those intending to employ such an amplifier. Lead storage cells are used for the A, B, and C batteries. The gassing which persists for some time following charging of the batteries is very troublesome. It causes vigorous and disturbing "kicks" of the vibration galvanometer. To avoid the delay of waiting for the gassing to cease, two sets of batteries

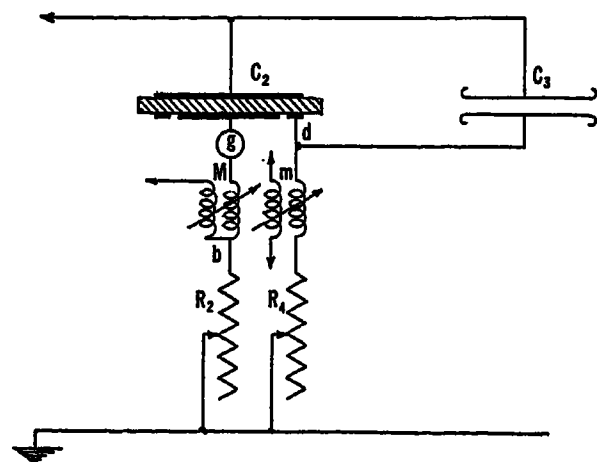


FIG. 3—SHUNTED-GUARD CIRCUIT BALANCE

are used with suitable switches for throwing on charge, or in service. Hence, it is always possible to have in service batteries which have attained a steady condition.

The galvanometer, amplifier, batteries, and resistances are within a wire enclosure (Figs. 1 and 7) to shield the apparatus from electrostatic induction. Since the screening is maintained at the galvanometer potential, the effects of capacitance to ground are minimized.

This screening does not shield electromagnetic disturbances. For example, stray magnetic fields produced by conductors carrying alternating current, by rotating field structures of alternators, and by spark discharges react readily on the vacuum tubes of the amplifier, causing trouble. An iron enclosure over the amplifier may shield against such disturbances. It is more desirable, however, to remove the source of the stray field.

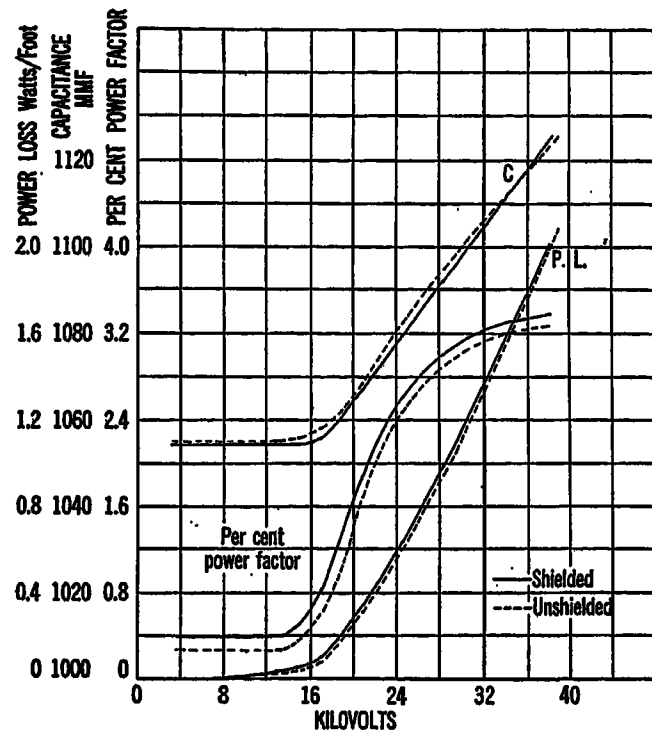


FIG. 4—EFFECTS OF SHIELDING 10-FT. LENGTH SINGLE CONDUCTOR CABLE AT 60 CYCLES AND 20 DEG. CENT

Mechanical vibration, such as is due to rotating machinery, may affect the amplifier. If the vibration is synchronous with the power supply, the balance with the amplifier may be false and differ appreciably from that without the amplifier. The authors have found that porous red rubber sponges under the amplifier eliminate vibration.

The amplifier may oscillate at high frequency, usually caused by capacitive feed back of the last tube

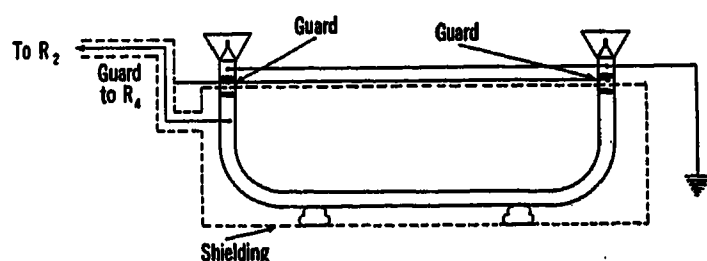


FIG. 5—METHOD OF DOUBLE GUARDING

to the first. The presence of conducting material, such as shielding, aggravates this difficulty by increasing the capacitive coupling. If near a powerful radio station, the amplifier is frequently affected by the high-frequency electromagnetic waves. Code signals from the Charlestown Navy Yard have been detected with our amplifier. Both of the foregoing effects are almost entirely eliminated by shunting a 1- or 2- μ f. condenser across the grid circuit of the input tube. Such con-

densers are virtually a short-circuit for the high frequencies, and do not cut down the sensitivity at power frequencies to any harmful extent.

SHIELDING THE AIR-CONDENSER, ITS LEADS, AND THE BRIDGE

Careful tests of our air-condenser which has already been described³ showed it to have an angle of defect of something like 9 min. Investigation showed that this comparatively large angle was due to the fact that the

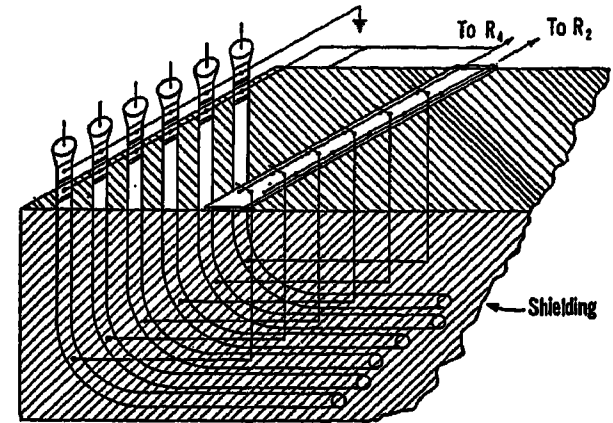


FIG. 6—CONNECTIONS OF CABLES IN CABLE RACK

guard plate surrounding the edges and back of the low-voltage plate of the air-condenser was grounded. Also, the low-voltage plate was connected to the bridge with a 20-ft. length of rubber-insulated, lead-covered wire, the sheath of which was grounded. The capacitance between the low-voltage condenser plate and its shield,



FIG. 7—ILLUSTRATION OF BRIDGE

and the capacitance to ground of this lead are considerable. The effect of these capacitances is to shunt R_1 with considerable capacitance. This has the effect of making C_1 appear to be a poorer condenser than it actually is. This matter has already been discussed before the Institute.³

This error is reduced by moving the bridge near the air condenser. Also, instead of using lead-covered

cable, the connection from the low-voltage plate to R_1 is made with a 1/16-in. (1.6-mm.) diameter brass rod centered within brass tubing 1 in. (2.54-cm.) in diameter, as shown in Fig. 1. (Also see Fig. 7.) The rod is held central by Bakelite washers spaced approximately 2 ft. apart. Hence, the capacitance of the connecting lead to ground is reduced to a very small value. Moreover, instead of grounding directly the guard plate and the brass tube, they are connected to ground through the secondary of a mutual inductance m' in series with a variable resistance R_3 , Fig. 1. The primary of m' in series with a condenser C_0' is connected from the high side of the voltmeter coil to ground. One of the adjustments of the bridge is to connect the detector between point a and the point c which is at one end of the secondary of m' . By adjusting R_3 , points a and c may be brought to nearly the same potential. However, owing to differences in power factor between the working plate and the guard circuit of the air condenser, points a and c cannot usually be brought exactly to the same potential by adjusting R_3 alone. The secondary of m' , however, may be made to introduce into the circuit an e. m. f. which is nearly in quadrature with the voltage drop in R_3 . Obviously, this e. m. f. may be made either to lead or to lag by varying the position of the secondary of m' . The magnitude of this e. m. f. is controlled by varying either C_0' or m' . Thus, points a and c may be brought exactly to the same potential and no error due to shunted capacitance across R_1 can occur. With the bridge used here, C_0' is of the order of $2 \mu\text{f.}$ and m' is approximately 25 millihenrys.

Also, to eliminate capacitance effects between other bridge members and ground, and to shield the low-voltage bridge elements from stray dielectric fields, the entire low-voltage side of the bridge is completely shielded by chicken wire, as shown in Figs. 1 and 7. This shield is connected to point c and its potential balanced to ground with the condenser shielding, by means of R_3 and m' . Hence, the bridge shielding is not connected directly to ground. For safety, however, four film gaps are used, Fig. 1.

SHIELDING THE CABLE

As in the case of the air-condenser arm of the bridge, capacitance between the cable sheath and ground, and capacitance to ground of the lead connecting R_2 to the cable conductor are equivalent to shunting R_2 with capacitance. Hence, it is desirable to shield this lead with brass tubing as with the air-condenser lead. Moreover, to eliminate the capacitance between cable sheath and ground and to prevent charges in the neighborhood having influence on the sheath, the cable is almost completely enclosed in screening of 1/4-in. square mesh wire, (Figs. 6 and 7). This shielding is connected to the brass tubing. Likewise, the ends of the cable sheath which serve as guards are connected to this wire shield. This entire metallic shielding system is con-

nected to ground through the secondary of a mutual inductance m and the resistance R_4 in series. (Fig. 1.) When the bridge is being brought into balance, the detector is connected between points b and d and the potential difference between these points is brought nearly to zero. As with the air-condenser, there is ordinarily a difference between the power factor of the cable proper and this guard circuit, which produces a phase displacement between the voltage drops across R_2 and R_4 . This prevents a perfect balance between points a and d unless the phase of the voltage between d and ground is in some way shifted. As with the air condenser, a simple and effective method of shifting this phase is to connect another mutual inductance m in circuit in the same manner in which m' was connected, (see Fig. 1). The primary of this mutual inductance and a condenser C_0 are connected in series across E_2 . If a voltmeter coil is not available, these series circuits may be connected across the primary of the test transformer or the secondary of a potential transformer.

The secondary of m is connected between R_4 and d . Again, this introduces an e. m. f. into this circuit which is nearly in quadrature with the voltage drop across R_4 . Hence, the phase balance, either lag or lead, is quickly made by merely rotating the secondary of m . Since both m and m' serve only to bring a guard circuit to the correct potential, it is not necessary to know the actual values of their mutual inductance. Hence, neither m nor m' need even be calibrated, although some type of indicating dial facilitates making the balance. To minimize the effect of stray fields on the amplifier tubes, it is desirable that these mutual inductances be made astatic.

The values of the capacitance C_0 and mutual inductance m depend on the voltage E_2 and frequency, as well as on the electrical characteristics of the guard circuit. Fortunately, this system is a very flexible one. With a given value of m , it is not difficult to find some value of C_0 which will give a balance. Moreover, since moderate losses in C_0 do not affect the operation of the system, paper condensers are perfectly satisfactory.

With the usual cable samples, with a frequency of 60 cycles and a 100-to-1 ratio of E_1 to E_2 , a sufficient range can be obtained if C_0 is from 0.2 to $2 \mu\text{f.}$ with the mutual inductance equal to 3 mh. With an 1100-to-1 ratio of E_1 to E_2 and this same value of m , it requires approximately $20 \mu\text{f.}$ for our system. For a given range of m , the value of C_0 varies inversely as the square of the frequency. Hence, with lower frequencies these values of C_0 and m must be modified accordingly.

With some samples, such as a 10-ft. cable length, the voltage between b and ground may be only 2 or 3 volts. If the capacitance between shielding and ground is small, this last balance may not be necessary. However, it is so easily obtained with the system just described, that now we always make this adjustment,

and at least one factor that might introduce error is entirely eliminated.

Sometimes with small samples, or when inserting resistance in series with a capacitance to introduce loss purposely, it may require a prohibitively large value of R_4 and of m or C_0 to bring the guard circuits to the proper potential. This difficulty is readily overcome by connecting a condenser C_3 to point d as shown in Fig. 3. C_3 may be a non-shielded air-condenser, a plate-glass condenser, (such as is described later), or even a piece of cable. It is seen that this connection amounts only to connecting more capacitance in parallel with the guard circuit. In the test of the E. T. L. condenser, which is described later, without C_3 , R_4 was of the order of magnitude of 95,000 ohms and no values of m or C_0 which were conveniently available would bring the guard circuit to balance. By using the plate-glass condenser, R_4 was reduced to 1030 ohms and also the guard-circuit balance was readily obtained. This connection also facilitates the balance when there are corona or "static" discharges in the guard circuit.

Another important function of this cable-sheath shield is to prevent any loss currents or any capacitance currents or any induced charges from high-voltage leads finding their way to the sheath, and hence, being included in the measurement. The effect of such shielding and non-shielding has already been described.⁴ Some investigations of this shielding effect have been made in our laboratories. It has been found that shielding *increases* the power loss and power factor, but decreases the capacitance. A typical curve, taken with a 10-ft., 500,000-cir. mil cable sample, with 8/32-in. wall of insulation, is shown in Fig. 4. With the exception of the change of capacitance, these effects are just the opposite of what would be expected; in fact, in the course of dielectric investigations, it has been observed that because of some unforeseen and obscure factors results frequently are the opposite of those anticipated. It may require a prolonged and painstaking investigation to discover these factors.

Feeling that this anomalous effect of increased loss with shielding might be due to some inherent peculiarity of their apparatus, the authors discussed the matter with one other laboratory. Careful tests with other apparatus showed this same effect.

Although this effect of shielding is small, an attempt was made to determine its causes, both by analyzing our bridge circuits and by upsetting the balances of R_3 and R_4 . An entirely satisfactory explanation of this phenomenon has not as yet been found, but the matter is still under investigation.

Sometimes at the higher voltages it is impossible to balance the guard circuit because of discharges to the end-bells and sheath, but this difficulty was overcome by the system of double guarding shown in Fig. 5. The end-bells and a short section of sheath are grounded directly. A second short length of sheath serves as the usual guard and is connected to the shielding and hence

to ground, through R_4 . The higher frequency discharges are thus shunted directly to ground and do not disturb the guard-circuit balance.

In order to expedite the testing of samples, we have constructed cable racks, Fig. 6, which hold six 10-ft. lengths each. These racks are mounted on casters. Hence, the cables can be moved about very readily and when temperature tests are to be made the rack can be rolled into the heating box. (See Fig. 7)

When this rack was first used, the test was conducted on a single cable, with the other five free. Although at first sight the results obtained appeared to be rational, slight variations at times aroused curiosity and led to investigation. The cause of these variations was soon discovered when a slight personal shock from one of the idle cable sheaths was felt, after the high voltage had been removed. These charges on the idle sheath were sufficiently large to cause considerable error in the measurements of the sample under test. All six cable sheaths are now surrounded by the shield just described. By means of single-pole double-throw switches, (Fig. 6) the guards, conductors, and sheaths of cables not under test are connected to this shield. The authors heartily concur in the conclusions of C. L. Kasson⁴ as to the absolute necessity of completely surrounding the cable sheath with metallic sheathing; if this is not done, induction from unsuspected charges on neighboring bodies may cause errors and give irrational results.

MEASUREMENT OF THE AIR CONDENSER

The air condenser (C_1), if properly designed and shielded, may have a very small angle of defect—less than one minute—and if a variable condenser having a fixed loss and known capacitance be available,¹ it is possible to measure this angle. Unless a current-measuring device be connected in series with either the air condenser or the cable the capacitance C_1 must be known. This is measured by means of a precision capacitance bridge, using low voltage and a frequency of 1000 cycles per second. It was found that the 1000-cycle measurement checked the 60-cycle measurement, and 1000 cycles is more convenient.

In making the measurement, the capacitance between the high-voltage plate and the low-voltage plate *only* must be measured. To do this, the relative potentials of all plates and shields must be the same as they are when in use. Hence, the shielding about the low-voltage plate must be at the same potential as the low-voltage plate itself, but must not be included in the measurement. Also, the capacitance of all other bodies, including the leads, must be excluded.

The connections used by the authors are shown in Fig. 8. R_1 and R_2 are two ordinary non-inductive resistances; C'_1 is a variable precision condenser; C_2 is a fixed air condenser; R_3 is a resistance for compensating for any differences of loss in bridge arms C'_1 and C_2 ; ordinarily it is not needed. R_4 is a slide-wire resistance used for obtaining the "Wagner ground."

The guard circuit is grounded permanently at S . A small capacitance C_4 between the high-voltage plate and ground is necessary to balance the capacitance of the guard circuit to ground (and also that of C_1 to ground with switch S at a), when the ground balance is being obtained.

The bridge is first balanced with switch S at a , which grounds the low-voltage plate of C_1 . C_1' and R_3 are adjusted until a balance is obtained. By connecting

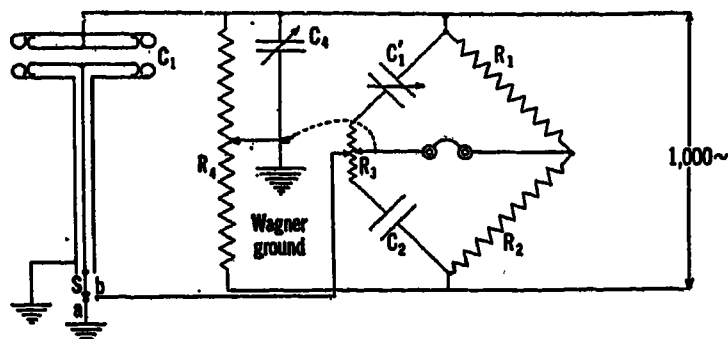


FIG. 8—CONNECTIONS FOR MEASURING THE CAPACITANCE OF A SHIELDED CONDENSER

the phones to the slide-wire contact, the ground balance is also made, adjustment of C_4 and R_4 being necessary. Switch S is then thrown to b , which shunts C_1 across C_1' . C_1' is now readjusted until the bridge is again balanced. The Wagner ground is also rebalanced. The capacitance C_1 is then the difference between the settings of C_1' .

From their experiences obtained in connection with dielectric research in general, the authors cannot over-emphasize the importance of investigating all potential and capacitance relations in the manner which has just been described. The neglect of some apparently minor detail may give an incorrect and misleading result.

TRANSFORMER RATIO AND PHASE ANGLE

The bridge gives a convenient and precise method for checking both the ratio and phase angle which exist between the total secondary voltage of the testing transformer and that of the voltmeter coil. The secondary voltage is usually assumed to be the voltage across the voltmeter coil multiplied by the ratio of secondary turns to voltmeter-coil turns. Also the voltage across the voltmeter coil is frequently assumed to be in phase with the secondary terminal voltage. These assumptions are based on the voltmeter coil's being so located in the secondary winding that it is linked by the same flux which links the secondary itself.⁵ That these conditions are not exactly true has of late been recognized.⁶ For some measurements, actual departure from the assumed conditions is negligible but compensation or correction may be necessary in dielectric-loss measurements of low power factor. In order to obtain some idea of the magnitude of these relations, ratios and phase angles in three testing transformers have been measured. The connections are given in Fig. 9. The air condenser C_1 , the primary of the mutual inductance M , and the

resistance R_1 are connected in series across the high voltage E_1 . A capacitance C_0 in series with a variable resistance R_0 is connected across the voltmeter coil, whose voltage is E_2 . To measure the phase angle between E_1 and E_2 , the phase angles of the two condensers C_1 and C_0 should be known. The angle of defect of C_1 is probably 0.5 min. or less. So far as we could determine, the angle of defect at 60 cycles of the best mica condensers of the capacitance of C_0 may be of the order of from 5 to 10 min. Hence, it became necessary to make a low-voltage air-condenser C_0 for this purpose. C_0 consists of 43 aluminum plates, 12 in. by 14 in. (30.5 cm. by 35.6 cm.), 1/16 in. (0.159 cm.) thick and spaced approximately 0.18 in. (0.457 cm.). This condenser has a capacitance of approximately 0.010 μ f. With the exception of four hard-rubber washers between the supporting rods and the two plates at each end there is no dielectric other than air between the alternate 43 plates. Although there were facilities sufficiently sensitive to measure angles of defect of small radio condensers, the measuring apparatus could not detect any angle of defect in this condenser.

The bridge is balanced by adjusting R_1 , R_0 , and M . Then

$$\frac{E_1}{E_2} = \frac{C_0 R_0}{C_1 R_1} \quad (4)$$

This assumes that the effect of R_2 and R_1 on the impedances of their respective circuits is negligible compared with their condenser impedances. With bridges of this type, the error is considerably less than 0.1 of one per cent.

If the angles of defect of C_1 and C_0 can be assumed equal, the angle between E_1 and E_2 ,

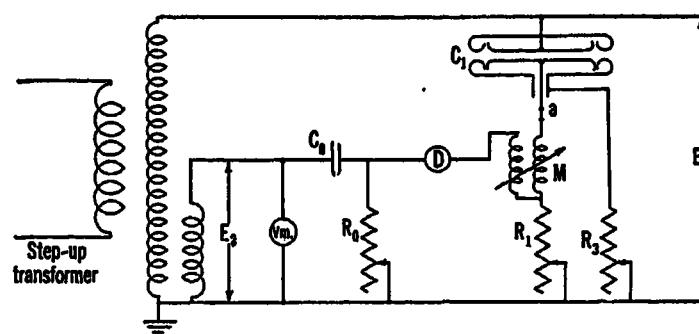


FIG. 9—CONNECTIONS FOR DETERMINING THE RATIO AND PHASE ANGLE OF VOLTMETER COIL

$$\beta = \tan^{-1} \frac{M \omega}{R_1} + \tan^{-1} \omega C_1 R_1 - \tan^{-1} \omega C_0 R_0 \quad (5)$$

All the above angles are very small. $\omega C_1 R_1$ is almost always so small as to be negligible. Hence

$$\beta = \frac{M \omega}{R_1} - \omega C_0 R_0, \text{ nearly} \quad (6)$$

If $\frac{M \omega}{R_1}$ lags I_1 and is greater than $\omega C_0 R_0$, E_2 lags E_1 .

If $\omega C_0 R_0$ is greater than $\frac{M \omega}{R_1}$, E_2 leads E_1 .

Below are a few typical data taken with a 15-kv-a., 50-kv. transformer. This transformer was made in the early days of transformer design and the voltmeter coil is not placed in the best position.

$C_0 = 0.01033 \mu f.$					$C_1 = 121.5 \mu \mu f.$		β (minutes)
Freq.	E_2	R_0	R_1	$M h$	Ratio = σ	E_1	+ E_2 leads - E_2 lags
No-load							
61	3.0	682.0	50	0.650	1155	3,465	- 7.7
61	10.0	676.6	50	0.517	1147	11,470	- 4.4
61	22.0	674.6	50	0.517	1144	25,200	- 4.4
45	8.0	674.0	50	0.470	1142	9,136	- 2.4
45	16.0	671.2	50	0.330	1138	18,210	+ 0.3
Load = 10 ft. cable, $C = 1215 \mu \mu f.$							
75	9	689.0	50	0.097	1166	10,500	+ 9.3
75	22	687.0	50	0.020	1165	25,630	+10.9
60	9	682.1	50	0.260	1155	10,400	+ 2.4
60	22	682.4	50	0.120	1156	25,430	+ 6.0
45	9	678.0	50	0.377	1148	10,330	- 0.5
45	16	677.2	50	0.317	1148	18,370	+ 0.6

The following data were taken with modern testing transformers.

15 kv-a., 250/50,000 volts							
$C_0 = 0.01007 \mu f.$				$C_1 = 580 \mu \mu f.$		Freq. = 60 cycles	
E_2	R_0	R_1	$M h$	Ratio = σ	E_1	β (minutes) E_2 leads	
No-load							
200	715.6	50	0.25	248.5	49,700	8.8	
140	715.6	50	0.25	248.5	34,790	8.8	
79	716.4	50	0.00	248.7	19,650	9.4	
Load = 100 ft. cable; $I = 0.096$ a. at 36 kv. Kv-a. = 3.5							
141	716.7	50	0.15	248.8	35,100	9.8	
120	717.5	50	0.15	249.1	29,900	9.8	
100	717.7	50	0.30	249.2	24,920	10.1	
40	717.7	50	0.30	249.2	9,970	10.1	
100 kv-a.; 250/100,000 volts							
$C_0 = 0.01007 \mu f.$				$C_1 = 580 \mu \mu f.$		Freq. = 60 cycles	
E_2	R_0	R_1	$M h$	Ratio = σ	E_1	β (minutes) E_2 leads	
No-load							
69	100	5756	5.0	99.90	58,900	10	
50	100	5753	5.3	99.88	49,940	9	
36	100	5753	5.3	99.88	20,710	9	
Load = 100 ft. cable. $I = 0.096$ a. at 36 kv.; kv-a. = 3.5							
36	50	2875	0.2	99.84	35,940	38	

Although the foregoing tabulation is not complete for the entire load and frequency range of the transformers, it does give the order of magnitude of the ratio change and the phase angle which may be expected under the conditions of no-load and of moderate condensive loads. When the voltmeter coil is properly located, the ratio varies only slightly for all voltages and loads. The value of this ratio should be determined with high precision, for in many methods of power measurement this voltage appears to the second power.

The magnitude of the phase angle is such that if the wattmeter be used for power measurement at low power factors, large errors must result. For example, a phase-angle difference of six minutes makes an error of 0.001 in the power factor and a corresponding error in the power. Good cables frequently have power factors as low as 0.4 per cent., so that this error in phase angle may well introduce 25 per cent error into the power measurement. Fortunately, most of the precision methods now used do not utilize the voltmeter coil in measuring the power. However, when a dynamometer is used, compensation is obviously necessary.

The phase-angle and ratio errors in potential transformers are much less than with voltmeter coils. However, potential transformers for these higher voltages are expensive, and two or three are necessary for the usual ranges of testing voltage. A sufficiently accurate method for measuring the high voltage directly is to connect a dynamometer in series with the air condenser C_1 . Then this voltage

$$E_1 = \frac{I_1}{C_1 \omega} \quad (7)$$

where I_1 is the current in the dynamometer.

With the lower voltages, our condenser did not have a capacitance great enough to give sufficient dynamometer deflection. Hence, a special plate-glass condenser, having a capacitance of $1880 \mu \mu f.$, was used.

CHECKING THE BRIDGE

Many factors which may not be apparent, and some which cannot even be foreseen, may introduce error into the measurement of dielectric loss. Hence, it is highly important to check and cross-check the measuring apparatus, and should any discrepancies be found, they should be investigated carefully.

A convenient check on the resistances, capacitances, and indicating instruments may be made by using the connections shown in Fig. 9. A deflecting dynamometer is connected at a between the low-voltage plate of C_1 and the mutual inductance M . C_1 may be either the cable or the air-condenser. By the authors both are used.

The current in the dynamometer

$$I_1 = E_1 C_1 \omega$$

From Eq. (4)

$$E_1 = E_2 \frac{C_0 R_0}{C_1 R_1}$$

$$\text{Hence,} \quad I_1 = E_2 C_0 \omega \frac{R_0}{R_1} \quad (8)$$

The four quantities C_0 , ω , R_0 , and R_1 are known. Below are given typical data which we have taken in making such measurements.

ω	E_2	R_0	C_0	R_1	I_2 m. a. from (8)	I_1 m. a. (observed)
377	25	1,004	$0.015 \mu f.$	109	1.300	1.295

It will be noted that the calculated and observed values of current are in almost exact agreement. This is not a power check, however, but the close agreement among the foregoing quantities gives added confidence in the use of the bridge for power measurements.

Already it has been pointed out that in these very low power-factor measurements, the measured values of power are proportional to the difference in phase angle (or its sine or tangent) between that of the reference standard, such as the air-condenser and that of the test specimen.⁷ If known losses are introduced into such a system, either into the air-condenser branch or the test-specimen branch, the measuring apparatus gives only the *change* in the phase angle. Hence, the absolute value of the power must depend on the value of the angle of defect of the air condenser. If this angle of defect be known, correction can of course be made. However, the introduction of a known loss into one or the other bridge arms does give a very good check on the accuracy of the apparatus in the measurement of phase difference. If the characteristics of the air condenser are known, the accuracy of the bridge in measuring this phase difference is also its accuracy as a power measuring device.

To insert a known loss in series with a capacitance of known characteristics and thus to determine the corresponding phase difference appears a comparatively simple matter. The authors thought so at first. Experience, however, has taught that to conduct such tests properly, a detailed knowledge of shunted capacitances, their magnitudes, and methods of either eliminating them entirely or of making their effect negligible, is very necessary.

A considerable source of error, however, may enter such measurement. In making the balance with r in circuit, the points b' and c , as is usual, are brought to the same potential by adjusting R_4 . (The mutual inductance m , Fig. 1, is also used but omitted in Figs. 10, 11, and 12 for simplicity.) Point a is at a higher potential than point b or b' by the voltage drop in resistance r . This is of the order of from 50 to 200 volts. Hence there now exists the effect of capacitance between the low-voltage plate a and its shielding S .

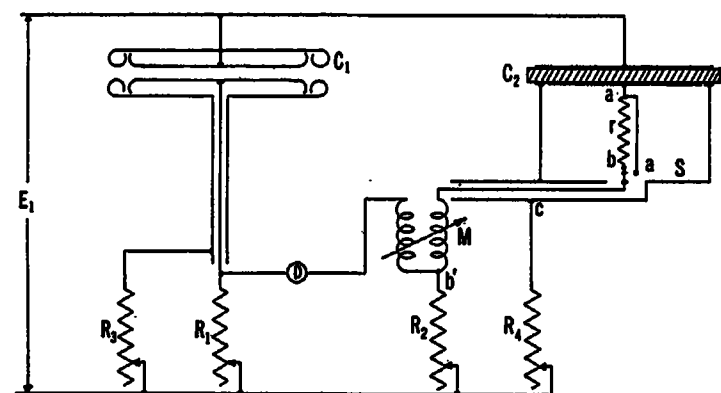


FIG. 10—INCORRECT METHOD OF CONNECTING SERIES RESISTANCE

Some of the current coming through C_2 , instead of flowing through r and R_2 in series, flows to ground through R_4 .

If the connections shown in Fig. 10 are modified, as shown in Fig. 11, it is possible to make small these capacitance effects which cause discrepancies. The resistance r is removed from within the shielding S and mounted in such a way that its capacitance to ground or to the shielding is negligibly small. The capacitance C_2 is made large so as to make any capacitance currents

E_1 , volts	R_1	R_2	R_3	R_4	M (Mh)	f	ω	I_2 (m. a.)	Power factor ($\sin \psi$)	Power watts,
$r = 0$										
19,300	770.1	50	1983	43,850	3.59	62.3	392	14.22	0.02815	7.73
$r = 12,410$										
19,300	769.8	50	1983	202	4.79	62.3	392	14.22	0.0375	10.28
$C_1 = 122 \mu \mu f.$										
$C_2 = 1878 \mu \mu f.$										
Increase of power = $10.28 - 7.73 = 2.55$ watts										
Power dissipated in r $(0.01422)^2 12,410 = 2.51$ watts										
Difference = 1.6 per cent.										
$\sin \psi_2 - \sin \psi_1 = 0.00935$ from (9)										
$C_2 r \omega = 0.00914$										

Consider first the bridge circuit shown in Fig. 10, which is the ordinary bridge circuit with a resistance r , connected to the low-voltage electrode of the test capacitance C_2 , so that it may be inserted in series with it.

The bridge is first balanced without r in circuit and the power factor $\sin \psi_1$ is obtained. The resistance r is then inserted in circuit and a second balance is obtained, giving the power factor $\sin \psi_2$. The increase in power factor for these small angles

$$\sin \psi_2 - \sin \psi_1 = r C_2 \omega \quad (9)$$

from r to the shielding negligible in comparison. The shielding balance is obtained by bringing points b and c to the same potential by adjusting R_4 , and also m (see Fig. 1), the condition of equal potential being determined by connecting detector D between b and c . For C_2 , a condenser having plate glass 0.5 in. (1.27 cm.) thick as a dielectric and tinfoil as the electrodes is employed. This condenser is immersed in oil. Below is given a set of typical data which we have taken, using these conditions.

These measurements have also been verified by

testing one of the E. T. L. standard condensers without and with a resistance in series, the connections being similar to those given in Fig. 11. Below are given data for one voltage:

E_1 volts	R_1	R_2	M (mh)	f	I_2 (ma)	Power factor (sin ψ)	Power watts
$r = 0$							
10,000	668.4	100	0.48	60	3.07	0.0810	0.0554
$r = 12,500$							
10,000	668.3	100	1.515	60	3.07	0.5710	0.1750
$C_1 = 122 \mu\mu f.$ $C_2 = 815.5 \mu\mu f.$							
Increase of power = $0.1750 - 0.0554 = 0.1196$ watt							
Power dissipated in $r = (0.00307)^2 \times 12,500 = 0.1178$ watt							
Difference = 1.5 per cent.							

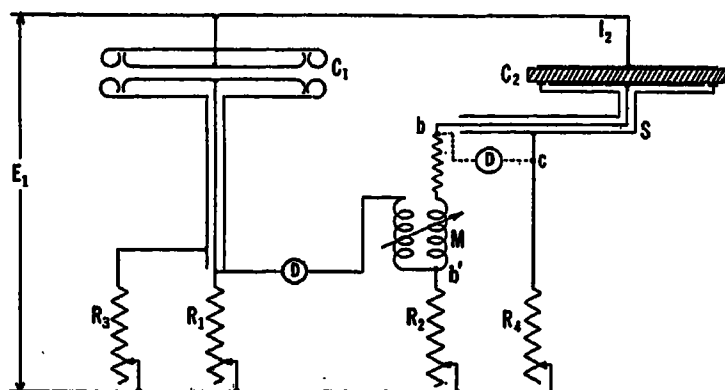


FIG. 11—CORRECT METHOD OF CONNECTING RESISTANCE IN SERIES WITH LOW-VOLTAGE PLATE

It was impossible to obtain these very close checks until the guard circuits were carefully balanced in both phase and magnitude by the methods which have already been described. In fact, it was due to the unexplainable discrepancies between measured and computed values which led to the study of further effects of guard-circuit balances, and the development of these methods.

To those who have had experience in the types of measurement which have just been described, the foregoing agreements are remarkably close, particularly when it is considered that with the plate-glass condenser, for example, the difference of 1.6 per cent in the values of power occurs in factors which are differences of two quantities, one of which is 75 per cent of the other.

It is interesting to note that with the plate-glass condenser ($r = 12,100 \Omega$) the difference of potential between the shielding S and ground, Fig. 11,

$$E_s = 0.01422 \times 12,460 = 177.2 \text{ volts}$$

With the E. T. L. condenser $E_s = 0.00307 \times 12,600 = 38.7$ volts.

It might be thought that the foregoing difficulties due to the capacitance of shielding could be overcome by inserting the resistance r in the high-voltage side of the condenser C_2 , as shown in Fig. 12. It then becomes necessary to shield completely the high-voltage plate b , as shown in Fig. 12. Otherwise there will be capacitance currents from this plate b to ground. Hence, all the current flowing through r does not flow through

R_2 . Even then, the same difficulty exists as was encountered in Fig. 10. With r in circuit, there is potential difference between the shielding S and the high-voltage plate b . Hence, current will pass from S to b to R_2 without going through r . This introduces error which is very difficult to eliminate.

Also the guard rings $a a$ and $a' a'$ must be sufficiently removed from the plates b and b' , or current from $a a$ may flow to b' or current from b may flow to $a' a'$. In the first case, too much current flows through R_2 ; in the second case, too little current flows through R_2 . These effects make it almost impossible to use the ordinary air-condenser for this purpose.

As a matter of interest, the 12,100-ohm resistance was connected in series with the high-voltage plate when making the tests with the E. T. L. condenser. The measured power in every instance was 13 per cent greater than the computed power. This was to be expected, since the currents in r and R_2 (Fig. 12) could not be equal. Some of the current in r is leakage current since there was no high-voltage guard-ring; also, some of the current in r goes to the low-voltage guard-rings. Hence, the current in r must be larger than that in R_2 and the two probably differ in phase by some indeterminate angle. Therefore, the measured power must necessarily be greater than the computed power.

HARMONICS

If a sinusoidal e. m. f. be impressed on the bridge circuit, such as shown in Fig. 1, no harmonics will occur so long as the capacitance and resistance of the system remain constant. When ionization does occur, however, the capacitance of the cable varies during the cycle, and harmonics, commencing with the third and extending well through the range of audible frequencies,

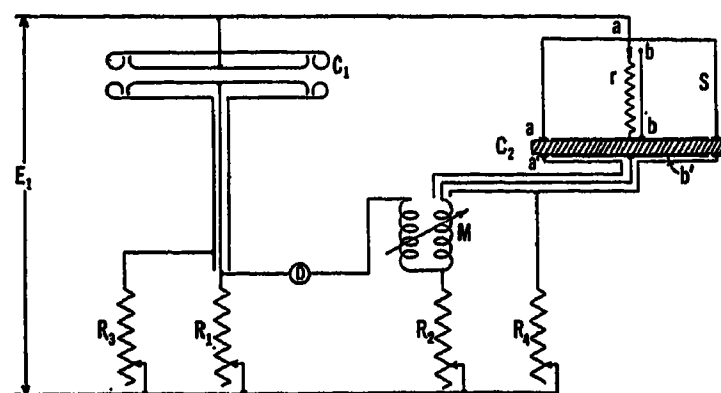


FIG. 12—METHOD OF CONNECTING RESISTANCE IN SERIES WITH HIGH-VOLTAGE PLATE

appear in the current wave. The theoretical effect of these has already been discussed before the Institute.⁸ In the ordinary cable, the magnitude of these harmonics is so small compared with the magnitude of the charging current, (and they add in quadrature), that it is doubtful if they have appreciable effect on the magnitudes of current and capacitance as determined by a bridge or by deflection instruments.

With a pure sine wave of voltage impressed on the system, these harmonics cannot contribute power because there is no component of their own frequency in the voltage wave. However, they do cause a dissipation of energy in the ionized air films, as is well known. Obviously this power must be taken from the power which is being supplied at fundamental frequency. It is not unlike the well known radio-telegraph circuit, through which very high frequencies are obtained from a low-frequency source by means of arc discharges.

These harmonic currents cause a voltage drop across resistance R_2 , Figs. 1 and 2. There is no corresponding harmonic voltage drop in R_1 . Hence, under the conditions of a sinusoidal wave across the bridge, the detector, when tuned for any harmonic, cannot be balanced. With a tuned galvanometer, such as employed here, it is possible to balance the fundamental, and then, by varying the tuning, to select, one at a time, the harmonics of the higher frequencies which cannot be balanced.

At one time these harmonics produced effects which baffled us temporarily. When testing some cables at low frequency, it was noticed that the mutual inductance became negative as soon as ionization began; that is, the cable apparently had become a source of energy. Since this effect was concurrent with a corona discharge in our end-bells, this discharge was at first blamed. Elimination of this discharge, however, failed to remedy the difficulty. After investigating and eliminating other factors which might possibly have caused the difficulty, it was found that a third harmonic in the impressed voltage wave was responsible. A 60-cycle generator was operating at 25 cycles. The higher saturation of the alternator iron introduced a small third harmonic into the impressed voltage wave. Hence, a third harmonic voltage appeared across R_1 , Figs. 1 and 2. This harmonic had no particular phase relation with respect to the third-harmonic voltage across R_2 due to ionization. Hence it was possible to obtain a balance with a negative value of mutual inductance. One of the factors that prevented a more rapid solution of the difficulty was the fact that the galvanometer had inadvertently been tuned for the third harmonic and its deflections were so large that it was thought to be tuned as usual for the fundamental.

CONCLUSIONS

1. The bridge used for precision dielectric-loss measurements should be shielded from electrical, magnetic, and mechanical disturbances.

2. The air condenser and the bridge leads should be shielded, and the shielding should be brought to the same potential as the conductors which it shields.

3. The cables should be properly shielded and this shielding brought to the same potential as the cable sheaths. Electric discharges should be prevented from entering any shielding circuit which is to be balanced. Methods of balancing shielding in both phase and magnitude are not difficult.

4. In measuring the capacitance of the air condenser, a method which maintains the potential of the guard plate always at the potential of the low-voltage plate must be used.

5. It is possible to measure with precision by means of a bridge circuit the ratios and phase angles of high-voltage transformers. With the voltmeter coil properly located, the ratio is practically constant at all voltages and loads. The phase angle may change considerably with load.

6. The precision of the bridge may be checked by the introduction of known losses in its arms. Extreme care must, however, be exercised lest leakage and stray capacitances give misleading results.

7. With a tuned galvanometer and a sinusoidal impressed e. m. f., harmonics probably introduce no error into the ordinary dielectric-loss measurement. Harmonics are troublesome, however, in that they may at times produce anomalous effects in bridge circuits.

The authors are indebted to Mr. P. H. Humphries of the Harvard Engineering School and to Mr. L. E. Cirella of the Simplex Wire & Cable Company for their assistance in obtaining the data given in this paper; to Professor H. E. Clifford of the Harvard Engineering School and to Messrs. D. W. Roper, F. M. Farmer, and W. F. Davidson of the Joint Paper Cable Research Committee for their suggestions in the preparation of this paper.

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Discussion

L. E. Cirella: For two years we have been using a bridge similar to that described by the authors. Profiting by their previous experience we have been able to avoid most of the difficulties described by them.

In the paper two reasons are given for the error made in measuring the phase angle of the air condenser, namely,

(1) Directly grounding both the condenser guard plate and the sheath of the low condenser plate lead wire, and

(2) The high capacitance from copper to sheath of the low condenser plate lead wire.

Tests we have made show that directly grounding the guard circuit is the principal cause of error. Increasing the capacitance of the guard circuit wires five times in either the condenser or cable guard circuit showed no measurable change in cable power factor as long as the R_2 and R_4 circuits were balanced. When the bridge is completely balanced the condenser guard and the low condenser plate are at practically the same potential and the same is true of the cable sheath and the cable shielding; therefore the capacitance current in shunt with the resistance arms of the main bridge is negligible.

Check tests were made recently with this bridge to show the effect of completely shielding the cable sheath of a sample. These tests gave slightly lower power factor, watts loss, and capacitance with complete shielding, indicating that the curves shown in Fig. 4 are not due to any inherent characteristic of this bridge. Looking at Fig. 1 it may be seen that shunting R_2 with a capacitance or upsetting the balance of R_4 will influence the capacitance, power factor, and watts loss of the cable sample. Tests were made on an unshielded sample of cable at 25 deg. cent. and curves similar in shape to those in Fig. 4 were obtained. Throughout this test the R_4 circuit was carefully balanced, R_4 being close to 6000 ohms. A second test made on the same sample with no shielding and R_4 at 4500 ohms gave curves similar to those for shielded cable of Fig. 4, that is, the power factor and watts loss were higher and the capacitance lower. This does not explain the curves of Fig. 4 satisfactorily, however, for it does not seem possible that two laboratories would have made balances with R_4 1500 ohms below the value for a balance when the sensitivity of this bridge is so great that 20 ohms off balance will cause a galvanometer deflection greater than 500 mm. In fact our tests suggest, in general, that the small differences shown in Fig. 4 are caused by slight differences in the cable temperature. For instance, three tests made in immediate succession on the same cable, the sheath of which was shielded, not shielded, and shielded showed continually increasing power factor regardless of the shielding condition.

H. W. Lamson: I have had occasion recently to develop a low-frequency amplifier intended for use in connection with a recording cardiograph. My purpose was to amplify low audible frequencies over a range from about 30 to 40 cycles per sec., and at the same time exclude as much as possible interference from 60-cycle mains or any harmonics thereof, or any other higher frequencies. This I was able to do with considerable success by using carefully designed transformers having tuned secondaries resonant at, say, 35 cycles.

It occurred to me that the interference difficulties which Professor Dawes experienced in his amplifying system might, perhaps, be largely eliminated by the use of a similar type of amplifier using, of course, transformers tuned to 60 cycles.

P. H. Humphries: Although the theory of the high-voltage bridge designed and used by Professor Dawes and his associates in dielectric research has been previously described,¹ I believe that a mathematical derivation of the bridge equations and an analysis of the conditions for balance would add to our understanding of its operation.

In Fig. 1 herewith is given the simplified bridge circuit which has already been presented before this Institute. The conditions for balance are derived on the basis of Maxwell's cyclic current equations.

Let the circuit constants be $Z_1 = R_1$; $Z_2 = r_1 - \frac{j}{C_1 \omega}$;

$$Z_3 = r_2 + j \left(L_2 \omega - \frac{1}{C_2 \omega} \right); Z_4 = R_2; M = j m \omega.$$

1. C. L. Dawes and P. L. Hoover, *Ionization Studies in Paper Insulated Cables*—I, A. I. E. E. TRANS., Vol. XLV, 1926, p. 142, Fig. 3.

Writing the voltage drops around the networks $c a d c$ and $b c d b$.

$$X(Z_2 + Z_3 - 2M + Z_G) - (X + Y)(Z_G - M) - I_B Z_2 = 0 \quad (1)$$

$$(X + Y)(Z_1 + Z_G + Z_4) - X(Z_G - M) - I_B Z_1 = 0 \quad (2)$$

A simplification of Equations (1) and (2) gives the two simple simultaneous Equations (3) and (4).

$$X(Z_2 + Z_3 - M) + Y(M - Z_G) = I_B Z_2 \quad (3)$$

$$X(Z_1 + Z_4 + M) + Y(Z_1 + Z_G + Z_4) = I_B Z_1 \quad (4)$$

The galvanometer current Y , the presence of which is evidence of bridge unbalance is given by (5).

$$Y = \frac{\begin{vmatrix} Z_2 + Z_3 - M & I_B Z_2 \\ Z_1 + Z_4 + M & I_B Z_1 \end{vmatrix}}{\begin{vmatrix} Z_2 + Z_3 - M & M - Z_G \\ Z_1 + Z_4 + M & Z_1 + Z_G + Z_4 \end{vmatrix}} \quad (5)$$

The condition of balance requires that the denominator in (5)

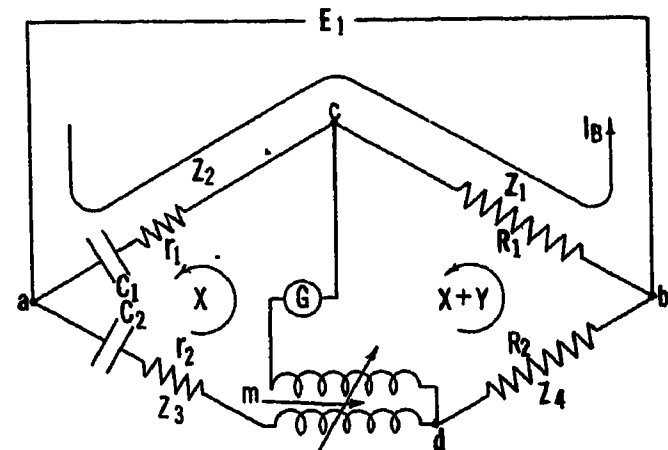


FIG. 1—DIAGRAM OF CONNECTIONS FOR DAWES BRIDGE

be zero. Hence from the numerator Equation (6) is derived.

$$Z_1 Z_3 - Z_1 M = Z_2 Z_4 + Z_2 M \quad (6)$$

Replacing the generalized bridge impedances in (6) by their complex values,

$$R_1 \left[r_2 + j \left(L_2 \omega - \frac{1}{C_2 \omega} \right) \right] - j R_1 m \omega = R_2 \left(r_1 - \frac{j}{C_1 \omega} \right) + j m \omega \left(r_1 - \frac{j}{C_1 \omega} \right) \quad (7)$$

From Equation (7) by equating the real parts:

$$R_1 r_2 = R_2 r_1 + \frac{m}{C_1} \quad \text{or} \quad r_2 = \frac{R_2 r_1 C_1 + m}{R_1 C_1} \quad (8)$$

From Equation (7) by equating the imaginary parts:

$$R_1 \left(L_2 \omega - \frac{1}{C_2 \omega} - m \omega \right) = - \frac{R_2}{C_1 \omega} + r_1 m \omega \quad (9)$$

Solving Equation (9) for C_2

$$C_2 = \frac{C_1 R_1}{R_2 + C_1 \omega^2 [R_1 (L_2 - m) - m r_1]} = \frac{C_1 R_1}{R_2 + k} \quad (10)$$

where

$$k = C_1 \omega^2 [R_1 (L_2 - m) - m r_1]$$

The second term in the denominator, k , is ordinarily negligible in comparison with R_2 as will be shown later, hence $C_2 = C_1 \frac{R_1}{R_2}$

The phase angle of the dielectric under test may be found as follows:

$$\tan \psi_2 = r_2 C_2 \omega = \left[\frac{R_2 r_1 C_1 + m}{R_1 C_1} \right] \left\{ \frac{R_1 C_1}{R_2 + C_1 \omega^2 [R_1 (L_2 - m) - m r_1]} \right\} \omega = \frac{(B + m) \omega}{R_2 + k}$$

where $B = R_2 r_1 C_1$

It will be shown later that in this type of work the term B may also be neglected, hence

$$\tan \psi_2 = \frac{m \omega}{R_2} \quad (11)$$

The original values for the capacitance and phase angle of the test specimen are too involved for practical application so certain factors as noted are neglected. It may be seen from the following calculations that the approximations are justified.

The following data were taken from measurement upon a 15-mil (0.038-cm.) air film in series with a 0.5555-in. (1.41-cm.) Pyrex plate, test area 17.25 sq. in. (111.3 sq. cm.) at a gradient across the air film of 120 volts per mil.

$C_1 = 122 (10)^{-12} f$; $r_1 = 0 \Omega$; $R_1 = 532.3 \Omega$; $R_2 = 2000 \Omega$; $r_2 = 3 (10)^6 \Omega$; $M = 0.220 h$; $L_2 = 0.800 h$; $f = 60 \sim$

Using these data above

$$k = C_1 \omega^2 [R_1 (L_2 - m) - m r_1] = 0.00535$$

a value which is insignificant when compared with R_2 .

$$B = R_2 r_1 C_1 = 0$$

It may be seen therefore that C_2 and $\tan \psi_2$, even in a case where a portion of the composite dielectric is subjected to very heavy ionization, are not affected by the approximations.

The theory of operation of the guard circuit Fig. 2 herewith is as follows:

The conditions for balance of this guard circuit whether it be an air condenser or test-specimen guard may be derived by the method employed for the bridge proper. These equations, however, are exceedingly involved and much time and labor is consumed in reducing them to the form where balance conditions may be readily noted. The circuit may be solved quite simply by means of a vector diagram, Fig. 3.

Let α = the phase angle of the bridge arm containing the dielectric under test.

When a diagram it is quite impossible to draw all vectors to

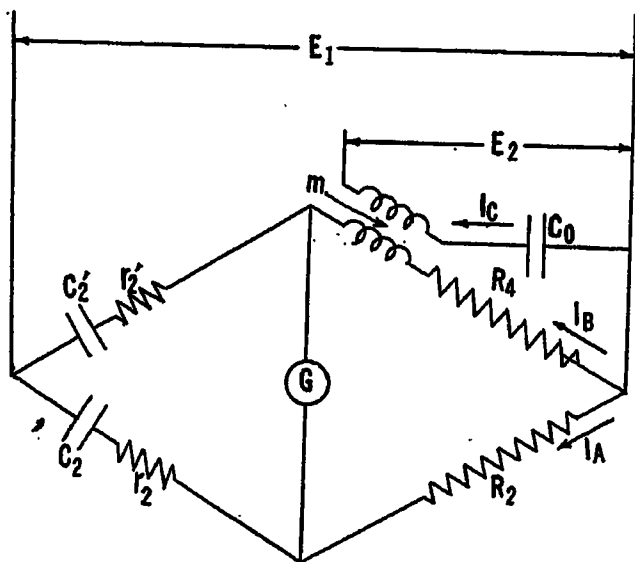


FIG. 2—DIAGRAM OF CONNECTIONS FOR GUARD CIRCUIT

scale such quantities as voltage drops across R_3 and R_4 and the shift in phase produced by the mutual inductance of necessity being exaggerated.

$$\alpha = \psi_2 - \psi_1 \quad (12)$$

$$\tan \alpha = \frac{I_C m \omega}{I_B R_4} \quad (13)$$

$$\tan \psi_2 = r_2 C_2 \omega, (R_2 \text{ negligible compared with } r_2) \quad (14)$$

$$\tan \psi_1 = \frac{I_B (R_4 + r_2')}{I_C m \omega + \frac{I_B}{C_2' \omega}} = \frac{I_B C_2' \omega (R_4 + r_2')}{I_C C_2' m \omega^2 + I_B} \quad (15)$$

In the expression for $\tan \psi_1$, $I_C C_2' m \omega^2$ is negligible compared with I_B , hence

$\tan \psi_1 = C_2' \omega (R_4 + r_2') = C_2' r_2' \omega$, (R_4 negligible compared with r_2').

Since ψ_2 and ψ_1 are both small angles and $\psi_2 - \psi_1$ is small we may write

$$\tan \alpha = \tan (\psi_2 - \psi_1)$$

or

$$\frac{I_C m \omega}{I_B R_4} = C_2 r_2 \omega - C_2' r_2' \omega \quad (16)$$

In the expressions for I_B and I_C the resistance R_4 and the

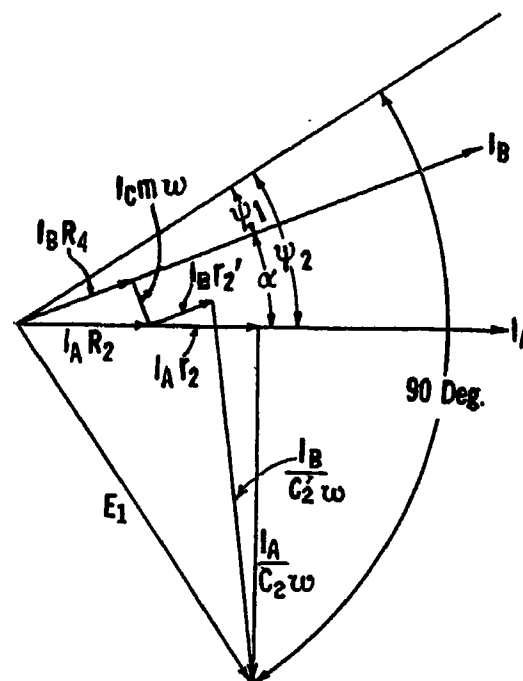


FIG. 3—VECTOR DIAGRAM FOR FIG. 2

reactance $m \omega$ are insignificant in comparison with the capacitive reactances in these arms, hence

$$I_B = E_1 C_2' \omega \quad \text{and} \quad I_C = E_2 C_0 \omega = \frac{E_1}{\sigma} C_0 \omega$$

Equation (16) then becomes

$$\frac{E_1 C_0 m \omega^2}{\sigma E_1 C_2' \omega R_4} = C_2 r_2 \omega - C_2' r_2' \omega \quad (17)$$

or

$$m C_0 = \sigma C_2' R_4 (C_2 r_2 - C_2' r_2') \quad (18)$$

In the past shields and guards have been referred to rather loosely and the use of them made in a haphazard "hope for the best" attitude. There remained much doubt regarding the efficiency with which they performed the functions for which they were employed. Messrs. Dawes, Hoover, and Reichard are to be warmly congratulated upon the methods which they have developed to bring the shielding and guards to the correct potential and the steps that they have taken toward clarifying the situation with reference to the proper use of shields and guards in such a difficult and poorly understood type of research.

C. T. Weller: In a discussion of my paper entitled 132-Kv. Shielded Potentiometer for Determining the Accuracy of Potential Transformers,² I was asked why we utilized shielded resistance instead of capacitance in the potentiometer or voltage divider.

Our principal conclusion in regard to the use of capacitance was that "capacitors of the types and ranges required were not in the same class as resistors from the standpoints of stability and accuracy. These views were confirmed, in general, by Dr. H. L. Curtis of the Bureau of Standards." I also stated that "it is obviously desirable to keep the size and the cost of testing

equipment at a minimum and it is hoped, therefore, that other laboratories will proceed with the necessary development work so that capacitance or impedance potentiometers will be available which are comparable with the 132-kv. shielded potentiometer in flexibility, stability, and accuracy as well as in voltage range."

It is evident from the paper by Messrs. Dawes, Hoover, and Reichard and from the discussion, particularly Professor Kouwenhoven's, that progress has been made (a) in the design and application of high-voltage capacitors and (b) in replacing the low-voltage mica capacitor previously used by an air capacitor.

I notice also that the authors recognize that harmonics are objectionable and capacitance tends, of course, to amplify them.

While I still feel that resistance is preferable to capacitance, inductance, or impedance for determining the accuracy of potential transformers, I should appreciate comments along this line by the authors and others interested.

T. F. Peterson: Mention has been made of the fact that it had been originally planned to have a paper on Errors in Loss Measurements by Dr. Ryan. I happened to have the good fortune to be associated with him in some of his work, and so have a little of the information which might have been included in such a paper. Inasmuch as it logically falls in the classification of errors in measuring dielectric loss, which Professor Dawes covered so thoroughly, I think it might be presented at this time.

One of the methods developed by Professor Ryan for measuring dielectric loss, particularly corona loss, is by means of a dynamometer wattmeter, using a high-resistance water column as a potential multiplier. A high-voltage transformer grounded at one end is connected to the two coils of the wattmeter, which is housed in a copper gauze shielding cage also at high potential. One coil of the instrument is connected to the transmission line by conductors which are shielded by surrounding pipes and which are maintained at the potential of the cage. The other coil, that is, potential coil, is connected by shielded conductors to a flowing water-column resistance. The circuit is essentially that of a wattmeter with a potential resistance multiplier, and, by reading current through the water column as well as the voltage across same, the multiplying factor may be determined.

As can be appreciated, the measurements at these low power factors at such high voltages were shrouded with all manner of insidious errors. H. H. Henline was the first to recognize the difficulties incurred by the slight difference in potential existing between leads to the line and water column and their respective shielding pipes. Since the leads were connected to the transformer by the impedances of the instruments through which current had to flow, and shields were connected directly, a difference in potential existed between the shield and conductor equal to the drop through instruments. This gave rise to charging current which, with the large charging current to the line, conspired to introduce great errors, all too deceptive because they were proportional to the voltage squared.

I worked up the mathematics of the circuit and we finally evolved the method of introducing compensating impedances between the transformer and shields which enabled us to establish zero potential difference between the conductors and shields. This made possible the elimination of one source of error.

There still remained another baffling difficulty with the set-up which introduced errors of unknown magnitude. The water column was supposedly pure resistance serving as a wattmeter multiplier by allowing a flow of current exactly in phase with the voltage. However, between the turns of the water column (about 6 ft. high, 8 turns) and from each turn to ground, there was appreciable capacity. The charging current to this (through the potential coil of wattmeter) though small, was in phase with the very large charging-current component to the transmission, and hence when these were multiplied by the instrument a very great error appeared. Though the existence was recognized and its value could be changed from a positive one to a

negative one by adjusting shielding rings around the coil, it was most difficult to determine when the error was zero without the use of a zero-loss condenser substituted for the transmission line.

At that time I introduced a method of determining when these errors were entirely eliminated from the reading, or which would allow of their elimination by computation. This consisted in taking a reading of loss with one setting of valves controlling the flow of water in column. Then the flow was cut down, thus allowing the temperature of the water to rise with a corresponding decrease in electrical resistance. In this way the current through the coil (in phase with voltage and with the loss component of current to line) could be altered in any way desired. Obviously the charging current of the water column remained constant since the configuration was not changed. A second set of readings was then taken, and by means of simultaneous equations the error could be eliminated and the true value of loss determined. It was, however, found more desirable to eliminate the error by adjusting the shielding of the water-column coil until doubling the current through this coil resulted in an exact doubling of the wattmeter reading. This condition obviously obtained when the error was zero and the measurement was truly that of the corona loss. Accomplishing this without the use of a zero-loss condenser was, to me, a decided advantage to this method and proved to be a great boon to the efforts then being made to determine corona loss exactly.

V. A. Thieman: Fig. 4 of the papers shows that careful shielding of a cable may actually increase the power factor and power loss. This effect is opposite to that which might be expected, and is contrary to results which have been obtained by others. As a part of a graduate thesis, I have conducted an extended investigation of such shielding effects. Two samples of cable which will be designated as *X* and *Y* were used for these tests. Cable *X* was a 600,000-cir. mil single-conductor cable with 12/64-in. (0.477-cm.) impregnated-paper insulation and cable *Y* was a 300,000-cir.-mil single-conductor cable with 14/64-in. (0.556-cm.) paper insulation. All tests were made at a frequency of 60 cycles. The bridge, the guarding, and the shielding were the same as those described in the paper. A rack similar to those shown in Figs. 6 and 7 was used. The entire wire screening, however, was fastened to frames which could be readily attached or removed from the rack. Also, further tests were made in which the active length of cable was shielded by winding varnished cambric around it for insulation and then wrapping wire screening closely about the cambric. The tests were made at a room temperature, which was approximately 19 deg. cent. Particular care was taken to locate the test cable remotely from all high-voltage wires except the single wire which is necessary to carry the voltage to the cable. For some distance this wire ran vertically upward away from the sheath.

In Fig. 4, herewith, are shown the characteristic curves obtained with cable *X*, and in Fig. 5, herewith, are shown similar curves obtained with cable *Y* with these cables in the rack. (Check tests taken at other times gave substantially the same results shown in Figs. 4 and 5.) The curves obtained with the wire screening wound around the cables agreed so closely with those shown in Figs. 4 and 5 that the small differences are scarcely perceptible.

With Cable *X* (Fig. 4) shielding gives lower values of power and power factor below the ionization voltage and greater values above the ionization voltage. Shielding decreases the capacitance. With Cable *Y* (Fig. 5) the reversed effects are obtained with the power and power factor whereas shielding scarcely affects the capacitance. In every case, however, the differences obtained with shielding and without shielding are small, and are much less than the changes which ordinarily occur due to physical and temperature changes in the cable between two consecutive tests.

Hence, these tests would appear to indicate that if cables of appreciable length when being tested are remote from high-

voltage conductors and other sources of induced charge, shielding has little effect.

In these tests, however, the low-voltage lead to the sheath had extremely low capacitance to ground, and the potential difference between sheath and ground was only of the order of 3 or

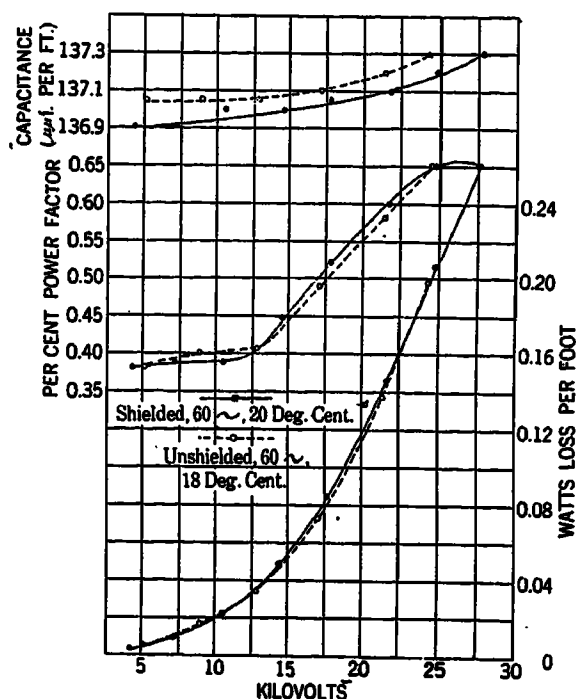


FIG. 4—TEST RESULTS OF CABLE X

600,000-cir-mil conductor with 12/64-in. insulation

4 volts, corresponding to a low value of R_2 of Figs. 1 and 2 in the paper. If it should be necessary to employ higher values of R_2 in order to obtain sufficient sensitivity, the voltage to ground would be increased. If, in addition, the capacitance of the lead to the sheath were high, it is possible that lack of shielding and

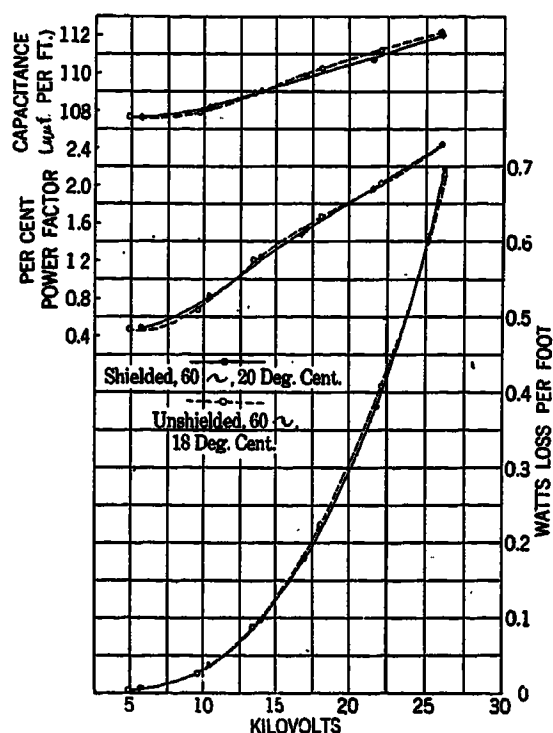


FIG. 5—TEST RESULTS OF CABLE Y

300,000-cir-mil conductor with 14/64-in. conductor

accurate balancing might introduce considerable error. Moreover, in view of the possibilities of induced charges occurring on cable sheaths, particularly where high-voltage sources are in the vicinity, as in cable-testing laboratories, I agree with the authors that shielding is always advisable, anyway.

C. L. Dawes: Dr. Curtis in Part III of his paper states that the wave form across the guard ring should be the same as that

across the guarded plate. However, if the wave forms do differ no error is introduced if a fundamental-tuned detector is used in balancing the potentials. Incidentally, as stated in our paper, corona and "static" discharges in the guard circuit do disturb the galvanometer when balancing but these effects may be overwhelmed by shunting the guard circuit with some invariable type of condenser such as an air condenser or a glass condenser.

It is very gratifying to learn that the results of the shielding tests made by Mr. Cirella are so nearly in accord with our own experience. In our earlier work the leads from the bridge arms to the air condenser and to the cable consisted of No. 14 A. W. G. rubber-covered wires having a lead sheath. Consequently there was considerable capacitance to ground. At that time we did not appreciate the quantitative effects of such shunted capacitance so that appreciable error was introduced into our measurements. In cable factories, however, it is frequently necessary to run such leads for considerable distance and the use of such lead-covered wire cannot well be avoided. Mr. Cirella has shown that if the shielding is properly balanced, leads of this type may be used without introducing appreciable error.

Mr. Cirella suggests that the discrepancy between the shielded and the unshielded curves in our Fig. 4 may be due to temperature changes occurring between runs. Mr. Humphries devoted several weeks to the study of this effect and special care was taken to eliminate temperature effect. For example, a test was made first with and without shielding; this order was reversed day after day but the relation of the curves did not change. The apparatus was sufficiently sensitive to detect easily the differences shown in Fig. 4. Hence these differences are not due to chance. Our conclusion now is that, although there were no high-voltage leads in the immediate vicinity of the test cable, there were other high-voltage conductors in the laboratory which may have influenced the cable sheath in such a manner as to have caused an apparent decrease in loss when the shielding was removed. The discussion of Mr. Thieman explains this matter further.

It is very interesting to learn that Mr. Lamson has developed a new type of sensitive detector which may be used to advantage with our type of bridge. We will undoubtedly take advantage of his suggestion that we try his galvanometer with our bridge.

Mr. Humphries' mathematical analysis is a distinct addition to the paper in that it shows concisely the effect of each of the bridge members on the operation and precision of the bridge. In his equation (18) he shows that the capacitance of the shielding-circuit condenser C_0 is independent of frequency whereas it is stated in the paper that the value of this capacitance varies inversely as the square of the frequency. This apparent discrepancy is explained by the fact that in Mr. Humphries' equations he assumes that the bridge members are invariable; that is, the cable is a fixed condenser in series with a fixed resistance. The statement in the paper is based on constant power factor. For example, in Fig. 3 shown by Mr. Humphries, the phase-dis-

placement angle, $\alpha = \tan^{-1} \frac{I_C m \omega}{I_B R_4}$. With constant volt-

age I_C is practically proportional to the frequency. Hence if α is fixed C_0 must vary inversely as the square of the frequency.

In answer to Mr. Weller's query as to our opinion of the accuracy of a shielded resistance potentiometer divider as compared with an air condenser, I am inclined to favor the air condenser, particularly after Mr. Peterson's presentation of the many sources of error that are encountered and the difficulties met in compensating for them. At this time it is quite certain that the phase angle of a well designed air condenser properly shielded is a minute or less. With a resistance divider and high voltage, considerable phase displacement may occur due to the mutual capacitance of the resistance and particularly to the capacitance to ground. By shielding, this last effect may theo-

retically be reduced to a small value but the shielding is not simple and so far as I know there is no simple method of checking the efficacy of the shielding. About 12 years ago we experienced considerable difficulty in developing a satisfactory resistance potentiometer for only 13 kilovolts. Attempt was made to shield in two ways, by a sectionized shield, all sections of which

were made to have the proper potential by means of suitable interposed resistances; and by a method not unlike that described by Mr. Peterson, where an inner glass tube of water was shielded by a concentric outer one. After considerable experimenting it was found advisable to abandon the resistance potentiometer in favor of the air condenser.

Shielding in High-Frequency Measurements

BY JOHN G. FERGUSON¹

Associate, A. I. E. E.

Synopsis.—The purpose and usefulness of shielding in high-frequency measurement are outlined. General principles of electrostatic shielding are developed as applied to simple impedances and to networks of impedances, particularly to bridge networks. Prac-

tical applications of these principles to the shielding of adjustable impedances, and in the construction of actual bridge circuits are described.

* * * * *

INTRODUCTION

SHIELDING of high-frequency measurement apparatus has for its immediate object the control of certain electromagnetic and electrostatic couplings, unintentionally introduced in the usual high-frequency circuit. These couplings are represented by stray admittances between the various parts of the system, either direct or to ground, and mutual impedances resulting from stray magnetic fields. In general, the control of these couplings is exercised for the purpose of attaining an accuracy of test that cannot be obtained so readily in other ways.

When we speak of electromagnetic and electrostatic coupling, it should be understood that these are simply component parts which together make up the total coupling which exists. They cannot be considered as existing independently of each other, and we cannot consider the shielding for one of these components without taking into consideration the effect on the other.

However, for the frequencies and impedances ordinarily used in communication work at least, this interdependence is small enough to allow us to consider the shielding problem for each type by itself, without getting into practical difficulties due to this connection. As a result, two types of shielding which are known as electromagnetic, and electrostatic shielding have been developed.

It may be argued that by extensive separation of the physical parts of circuits and apparatus, any couplings may be decreased in value, and in consequence errors caused by them can be reduced, thus eliminating any need for shielding. But there are obvious limits to the extent to which this method can be employed practically. In the case of electrostatic coupling to ground, it is scarcely of any value, and in any case, excessive separation of the parts of a circuit introduces other errors due to the length of the wiring involved. Accordingly, it is usually necessary, where the maximum accuracy is desired, to have recourse to shielding.

The principles involved in the application of electromagnetic and of electrostatic shielding are quite dif-

ferent. In the case of electromagnetic shielding, the methods used have for their object the elimination of all couplings from the unit shielded to all other apparatus; thus, if perfect shielding were possible the unit would have no coupling to any other parts of the circuit. It is never possible to accomplish this in the case of electrostatic shielding. Any electrical apparatus will have electrostatic coupling to any other apparatus in the vicinity and particularly to ground. The addition of shielding always introduces additional electrostatic coupling from the apparatus to the shield and the shield usually has more coupling to other equipment and to ground than the apparatus had before shielding it. Consequently, the principles of electrostatic shielding are mainly a matter of controlling this coupling in such a way that it has the least harmful effect in the circuit even at the expense of increasing its actual magnitude, rather than a matter of eliminating it entirely. For this reason electrostatic shielding requires much more extensive consideration and this paper is, therefore, devoted mainly to it, the principles of electromagnetic shielding being covered only briefly.

PRINCIPLES OF ELECTROMAGNETIC SHIELDING

The necessity for electromagnetic shielding is limited practically to wound apparatus such as coils and transformers. It may be reduced to a minimum by using high permeability core material wherever possible in coils and transformers, and by using some form of closed core such as the toroidal type. By these means stray fields may be reduced to a relatively low figure. However, there are cases where the remaining coupling may be objectionable and it is then necessary to use shielding to reduce still further the amount of these stray fields.

Two types of shielding may be used. A high permeability material may be used for the purpose of short-circuiting the stray field. The principles of this method of shielding are described fully in another paper and will not be considered further here.

In the case of air-core coils, which are often of the solenoidal type since the advantage of using the toroidal form is less in this case, and for coils used at very high frequency where heavy magnetic material is not so effective, shields of non-magnetic material may be used to confine the field by the effect of eddy currents. For these shields, a material of high conductivity is used, usually copper, and the principal consideration is the

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Part 3 of a Symposium of six papers on Shielding in Electrical Measurements.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

spacing of the shield from the coil rather than the thickness of the shield itself.

There is always a loss in efficiency due to the losses in the shield, and this loss is greater the closer the shield is placed to the coil; that is, the stronger the field in which the shield is placed. However, even with solenoidal air-core coils, very effective shielding may be attained by moderately thick copper shields, spaced about the distance of a diameter from the coil.

PRINCIPLES OF ELECTROSTATIC SHIELDING

In both theory and practise, all measurements assume that between different terminals or junction points of the system there are impedances having values known to a degree of definiteness consistent with the accuracies sought in the test. In an unshielded circuit, it will generally be the case that the elements connected by the various terminals or junction points will not provide impedances so definitely known, or, in other words, will not carry all of the current flowing between the points in question.

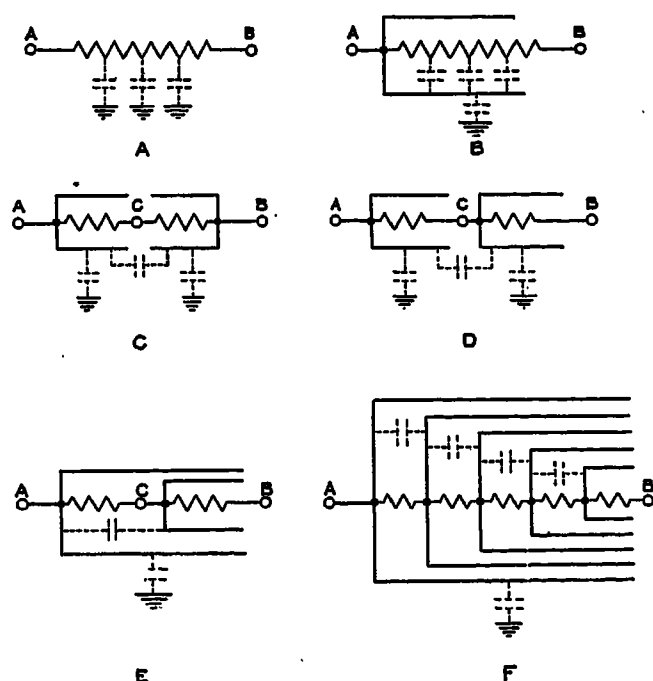


FIG. 1—METHODS OF SHIELDING SERIES IMPEDANCES

Resistors. In the case of the simple resistor such as pictured schematically in Fig. 1A, there are admittances from different parts of the conductor to other parts of the whole system and in particular to ground. These, of course, act to modify the effective impedance between the terminals and as they vary with the location of the resistor, the result is that its effective impedance is variable and known only for the location in which it has been calibrated. One of the first objects to be accomplished by shielding is to remedy this type of indefiniteness of value. This is done by mounting the elements within a shield of conducting material and in fixed space relation thereto, as shown in Fig. 1B. Thus, the circuit element has direct admittances only to the shield and as these are of fixed value the terminal to terminal impedance becomes independent of the location of the shielded element.

If, then, we connect the shield to any fixed point in

the circuit element such as one terminal, all of the current transferred by the shield admittances passes to or from the circuit at this particular point. This concentration of admittance enables the ready evaluation of the effect produced by it when the element is used in conjunction with others in a complete measuring system. We may summarize all of this to form a fundamental rule of shielding; *viz.*, "the association of an element of a system with a shield so that all admittances from the element to other parts of the system or to ground are confined to one terminal."

If it is possible to connect such an element in a circuit so that the terminal to which the shield is connected is grounded, all variable admittances will be eliminated completely.

Series Impedances. In the case of two impedances in series as shown in Fig. 1C, shielding may be accomplished by connecting one shield to terminal A and the other shield to B. In addition to the effects described for a single impedance there will then be admittance between the two shields which will depend on the position of the apparatus. This admittance is slightly more objectionable than admittance from shield to ground, since while we may ground either A or B, there will always be an admittance from one shield to ground which will be variable.

The shields may also be connected as shown in Fig. 1D, in which case the admittance between shields appears across the first impedance. If now we extend the shield connected to A to include the other shield as shown in Fig. 1E, we have introduced a fixed admittance across A C and have variable admittances to ground from A. The admittance across A C is not objectionable in the case of a capacitor since it may be considered simply as an addition to it, but it has the effect of increasing the phase angle of a resistor, and in the case of an inductor, it increases the effective inductance and resistance variation with respect to frequency.

If this combination of impedances can be grounded at A we have a complete system having no variable admittances. The principle may be extended to include any number of series elements, the effect being to place admittances across all of the elements but one, and to enclose the whole system in one outer shield. Such a system for five elements in series is shown in Fig. 1F.

Parallel Impedances. The shielding of parallel impedances is comparatively simple, since any number may be shielded individually and the shielding all connected to the same point. In reducing the shielding of multiple impedances to the simplest form the question arises whether it is sufficient to include them in a single shield or whether in addition they should be shielded from one another. If they are not shielded from one another there will be distributed admittances between them which may cause errors. Preferably each should be shielded individually. Fig. 2 shows such a shielding system for capacitors in parallel.

By following the procedure outlined above, it is com-

paratively simple to apply shielding to any combination of impedances in series or in parallel in such a way that we will have all admittances to external conductors from the shielded elements concentrated at terminals or junction points of the system.

Circuit Shielding. In many cases it is impossible to connect the above combinations in a given circuit so that the outer shield is grounded. In such cases it is necessary to determine from the position of the network in the system the effect of admittances from the shield to other shields and to ground. To illustrate, let us take the simple bridge circuit shown in Fig. 3. The four impedances constituting the arms each may be considered as any combination of individual impedances. With the shields connected as shown, the total admittances are reduced to three; between B and D and from B and D to ground. These admittances do not affect the bridge balance and, therefore, are not objectionable. However, if we add input and output circuits and follow the same system of shielding, we get the result shown in Fig. 4. In this case it is impossible to concentrate all of the admittances at B and D . Neglecting for the present the ground at D , we have added variable admittances from A to B , to D and to ground. The only way of overcoming this difficulty is

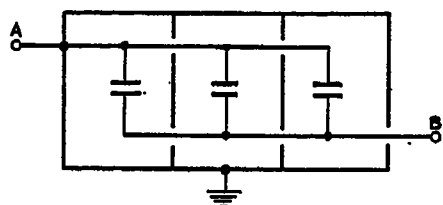


FIG. 2—METHOD OF SHIELDING PARALLEL IMPEDANCES

to use double shielding as shown, adding an outer shield to the impedance across A C and connecting it to D . This puts a fixed admittance across A D , but as we have not made any distinction between the four arms of the bridge, this admittance may generally be placed across an arm where it can be taken care of satisfactorily. If in addition we ground D , the admittances reduce to a single one from B to ground.

Admittance to Ground of Unknown Impedance. From the above it would appear that the general bridge circuit is susceptible of a simple complete solution, since the shielding shown in Fig. 4 is equally applicable to all cases. This would be true if the unknown impedance to be measured in the circuit had no admittance to ground. This is usually not the case. We generally have an additional requirement, that the potential condition with respect to ground of the impedance during the measurement be defined in some way.

If the impedance can be connected across one arm of the bridge and its value is desired with one terminal grounded, the circuit shown is satisfactory. However, these are special conditions, and where the impedance to be measured forms only part of the total series impedance of an arm, or where the potential requirements are different, such as the requirement that the coil be

measured with its terminals at equal potential to ground, the bridge shielding becomes a more serious problem.

In general, the question of selecting the most suitable system of electrostatic shielding for a specific test circuit, resolves itself into a determination of the most advantageous location of the admittances which, as

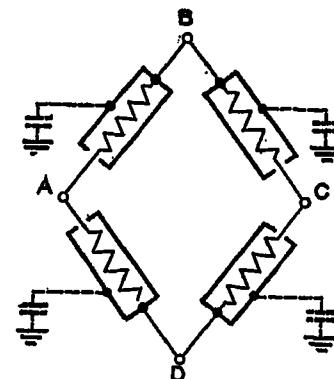


FIG. 3—BRIDGE NETWORK USING SHIELDED IMPEDANCES

described above, have been arranged to terminate at certain terminals or junction points. The facts which need to be taken into consideration are usually so varied that no general rules can be established. A few typical examples in which shielding is applied with considerable success will, therefore, be taken and the selection of suitable shielding for these circuits discussed.

EXAMPLES OF ELECTROSTATIC SHIELDING

Adjustable Resistor. An adjustable resistor usually takes the form of a dial box in which there are from one to six dials arranged in series in decade formation. Each decade considered by itself is no more difficult to shield than a single resistor. The admittance of the shield, however, has a different effect at each step which

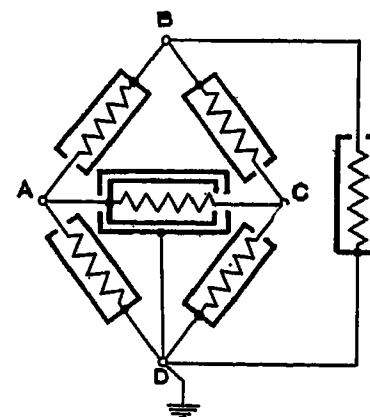


FIG. 4—COMPLETELY SHIELDED BRIDGE NETWORK

means that the phase angle varies with the setting of the dial. If the admittance to the shield is small, this effect will not be very great and in any case it is always the same for a given setting and hence may be included in a calibration.

In shielding several decades in series, admittances between decades are introduced. Effects due to these admittances can be taken care of completely by the use of nested shields as already shown in Fig. 1F. For a resistance box of five or six dials, this type of shielding becomes prohibitive from a size and cost standpoint and in consequence such shielding is usually not at-

tempted. The use of a single shield for all decades of a resistor means that the impedance of two or more dial settings is not exactly equal to the sum of the impedances of each setting by itself. If the difference is appreciable the only alternative to the expensive type of shielding mentioned above is the use of a calibrated value for every combination of dial settings. This error in additions is smaller the lower the resistance, and usually may be neglected for values below 100 ohms.

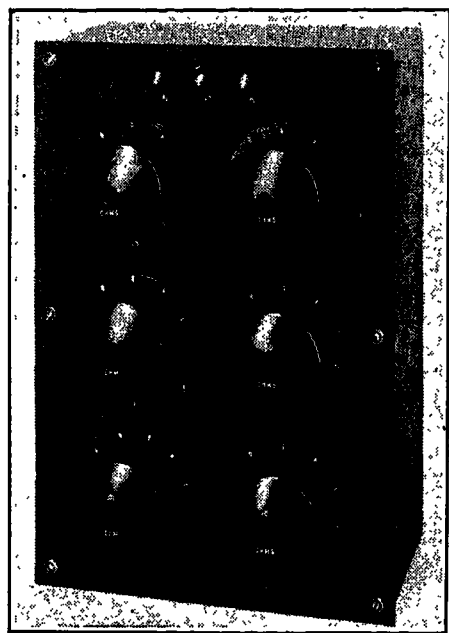


FIG. 5—SIX-DIAL SHIELDED ADJUSTABLE RESISTOR

The decades are ordinarily connected in series in ascending order of magnitude. The shield should always be connected to the low end, that is, to the terminal to which the decade of smallest value is connected. The reason for this may be explained as follows: the admittance from any decade to the shield is a function of the dimensions of the dial switch rather than of the resistance value. Consequently, all dials have approximately equal admittance to ground. It is desirable that the total admittance to ground be a minimum across the higher resistance settings. This requires that the low resistance dials be connected between the high dials and the shield; that is, the shield should be connected to the low end of the box.

In the actual construction of such a resistor it is essential that the shielding be complete, particularly at the dials. Since the effect of the hands in operating the dials is more variable than any other coupling, it is of very little value to place an unshielded dial box in a metal shield which allows admittance from the hand of the operator to the circuit.

An example of a six-dial resistor in a complete single shield is shown in Fig. 5. The box itself and the panel are of metal and the construction of the dials is such that there is a continuous metal shield between each dial head and the switch proper which it controls.

As stated previously, the effect of the shield on the performance of the resistor is to increase the phase angle of the higher resistance values. In the case shown the

admittance introduced by the shielding is of about the same value as the total admittance distributed in the coils themselves and from the coils to the switch parts.

Adjustable Inductor. The same considerations apply to an inductor as to a resistor except that on account of the larger physical size of the former, larger admittances are associated with it and for that reason it is usually necessary to use nested shields. Fig. 6 shows a standard inductor consisting of three decades and an inductometer using four shields. The three top panels have been removed, showing the method of nesting the shields, and the construction used to bring the dial controls through the shields. The shielding of this unit is not complete in that the fourth shield (the outer one) does not extend over the top. This is allowable as the admittance from the third shield to ground is across the inductometer and any variation in it has little effect, particularly as the final balance is obtained with the inductometer, thus eliminating variations due to the hands of the operator, which occur in operating the other dials.

The admittance between shields is considerable, but due to the method of construction, the largest admittance is across the smallest inductance and there is no intershield admittance added across the highest decade. Accordingly, the effect is not so serious as might be thought at first glance.

In the case shown, the inductometer and the lowest decade are generally used only in combination with the higher dials, and under these conditions they are not used at sufficiently high frequencies for the admittance shunting them to have much effect. The greatest effect of the admittance introduced by the shielding usually occurs when the second highest dial is used at a



FIG. 6—THREE-DIAL SHIELDED ADJUSTABLE INDUCTOR

high frequency with the high dial set on zero. However, the admittance introduced across this decade is not appreciably larger than the distributed admittance across the coils. The shielding, therefore, does not limit the range of these inductance standards to any great extent.

Adjustable Capacitor. The units of an adjustable capacitor are practically always connected in parallel and the problem of shielding them is that of shielding a

single capacitor. It is desirable to shield the decades from each other if the capacitances are small as this facilitates calibration and is easily effected. Where the capacitance is large,—say over $10,000 \mu\mu f$.—this precaution is unnecessary. The capacitance introduced from the shield to the units has the effect of increasing slightly the value of each dial setting. The form of construction of the shielding is similar to that of the resistor shown in Fig. 5.

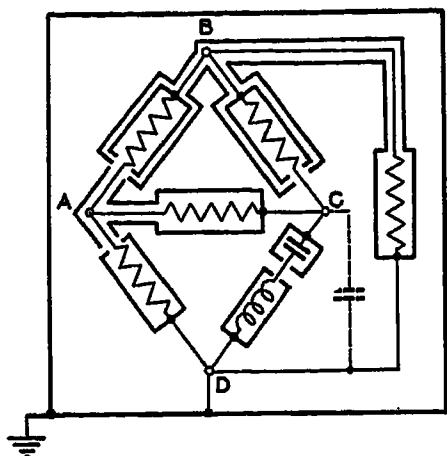


FIG. 7—SHIELDED RESONANCE BRIDGE NETWORK

Bridge Circuits. The general principles of bridge shielding have been discussed by Campbell³ and the equal ratio-arm comparison bridge has been discussed in detail by Shackelton.⁴ The mechanical construction of the bridge itself exclusive of standards is simplified by the fact that there are comparatively few dials to be brought through the shielding.

This bridge with the standards described above may be used for a wide variety of measurements. A rather simple modification is the so-called resonance bridge, in which the bridge unit is an equal ratio-arm comparison

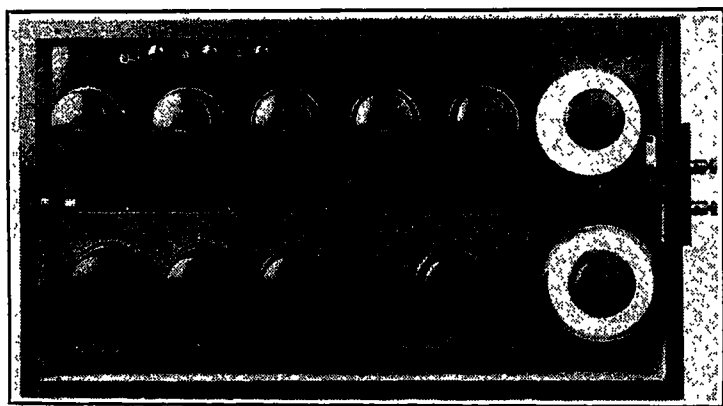


FIG. 8—SHIELDED RESONANCE UNIT, TOP PANEL REMOVES

type, and a resistance is balanced in one impedance arm against a capacitance and an inductance connected in series in the other impedance arm. The balance is usually effected by adjusting the resistance and capacitance.

The shielded circuit of such a bridge is shown in Fig. 7.

3. G. A. Campbell, "The Shielded Balance," *Electrical World and Engineer*, April 2, 1904, p. 647.

4. W. J. Shackelton, *A Shielded A-C. Inductance Bridge*, A. I. E. E. JOURNAL, Feb. 1927.

The capacitance from *C* to *D* introduced by the shielding may be compensated for in the usual way by the addition of an equal capacitance across *A D*. In this circuit, the coil is usually measured under the condition of one terminal at ground potential. Thus, *D* is shown strapped to the ground shield. For this case, the shielding may be simplified considerably. Fig. 8 shows the mechanical construction of the combined resistance and capacitance standard used with the bridge unit for these measurements. The unit is shown with the top of the outer shield removed. The capacitance, in accordance with the shielding diagram, is double shielded, while the resistance requires only a ground shield.

Another bridge of the comparison type but using capacitance ratio arms is described by Kupfmüller⁵, including a complete description of the shielding involved.

A bridge of the general comparison type having self contained standards of resistance and capacitance is shown with top panel removed in Fig. 9. It may be

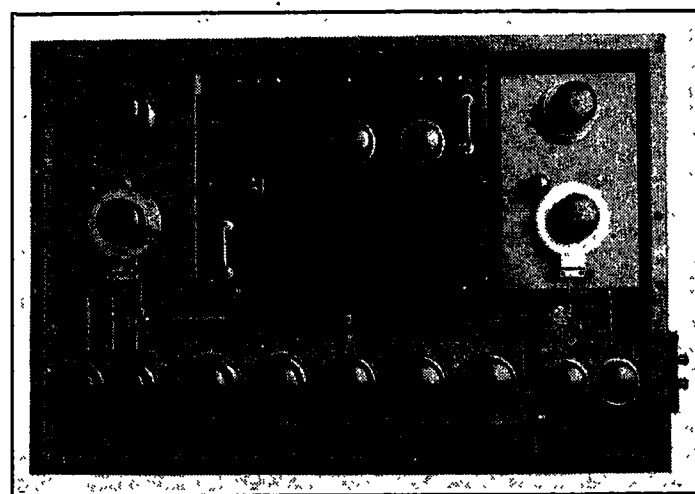


FIG. 9—SHIELDED COMPARISON TYPE BRIDGE, TOP PANEL REMOVED

used for a wide variety of measurements such as series or shunt resonance, and direct comparison, by using the switches controlled by the small dials on the extreme left and right to throw the standards into various combinations.

Another bridge circuit which is interesting from the shielding point of view is the Owen bridge.⁶ This is a skew bridge in which the ratio arms are 90 deg. out of phase instead of being equal. For this reason any admittance introduced in one arm by the shielding cannot be compensated for by any equal admittance in another arm. Two methods of taking care of this admittance may be used. It may be concentrated in the arm consisting of a capacitance and considered part of it, or an admittance across one impedance arm may be compensated for by a resistance across the other impedance arm. Both methods have been used in the construc-

5. Von K. Kupfmüller, "Über eine Technische Hochfrequenz Messbrücke," *Elek. Nach. Tech.*, September, 1925, pp. 263-270.

6. D. Owen, "A Bridge for the Measurement of Self Inductance," *Proc. Phys. Soc. London*, October, 1914.

tion of these bridges. A more detailed discussion of the shielding involved in this type of bridge is contained in a previous paper by the present author.⁷

Details of Construction So far, we have discussed the admittance introduced by the shielding without going into details as to the form which this admittance takes, although it has been broadly assumed that it is principally due to capacitance. Since it generally forms an integral part of the measuring circuit, it is obvious that as much consideration should be given to it as to the rest of the circuit. While the admittance is due essentially to capacitance, the necessary supports introduce a certain amount of conductance which causes some difficulty in obtaining compensation.

For instance, in the typical equal ratio-arm bridge circuit where the admittance across one arm requires compensation in the other arm, it is a simple matter to use an adjustable condenser for the compensation of capacitance. However, if the conductance is left uncompensated it may cause considerable error, particularly in the measurement of high impedances at high frequencies. For this reason, it is desirable that all shields be supported by insulating material of the highest quality such as hard rubber, glass, or quartz and that only the minimum amount necessary for satisfactory mechanical support be used.

It will be noticed in Fig. 9 that the wiring is shielded by brass tubing. This shielding is insulated from the conductor by means of bushings, only enough being used to insure that the conductor and shield do not change their relative positions with respect to each other. The insulating bushings used most generally are either hard rubber or glass beads.

Even after taking these precautions, it has been found necessary for the highest precision work at the highest frequencies, to introduce a conductance compensator in the form of a small adjustable condenser in which the dielectric is an insulating material such as phenol fiber. By this means the amount of conductance in one arm may be varied to obtain correct compensation. The balance, once obtained, does not vary appreciably with frequency. Such an adjustment is used with the bridge shown in Fig. 9.

In bridge input and output transformers, which must generally be double shielded, the shielding is rendered more difficult due to the requirement of a low conductance between shields. This demands a much more expensive construction than the simple requirement of complete electrostatic shielding.

Limitations of Shielding. Having discussed the uses and advantages of shielding, it may not be amiss to discuss briefly some of the limitations. As already brought out the introduction of shielding always brings with it some additional admittance. Since this admittance is a function of frequency it is natural that

shielding should introduce more trouble, the higher the frequency. However, it is also equally true that the stray admittances, due to lack of shielding, introduce more trouble as the frequency is increased.

In general, it may be said that if shielding a circuit is found to have a definite advantage at moderately high frequencies, it will have an advantage up to the maximum frequency at which the circuit is used. The principles outlined already apply over the whole range of communication frequencies. Where shielding is found to result in frequency limitations it is due to the added admittance introduced with it and not due to inherent defects in the principles involved.

The shielding may, in special cases, limit the maximum frequency at which the circuit will operate; but in such cases it can usually be taken for granted that even if the circuit would operate at higher frequencies without shielding, the accuracy of the results would be highly questionable. Examples of limitations of shielding may be given using the apparatus already described. Take the case of the resistor shown in Fig. 5. The admittance across the resistances results in objectionably high phase angles and an effective change in the resistances at very high frequencies. While this effect would be present even though no shielding were used, the shielding increases it and therefore limits the maximum frequency at which the apparatus can be used from the standpoint of this type of error. The same limitation occurs in the case of the inductance standards, only it is more serious due to the large physical size of these standards. The exact type of limitation here is that the individual units increase in inductance due to the admittance across them to such an extent that the difference between them cannot be bridged by the next lower decade, thus rendering it impossible to obtain certain values of inductance by any dial combination.

In the case of a symmetrical bridge, the principal limitation is the shunting effect of the admittance introduced across the impedance arms. This becomes so large that at frequencies in the order of 100 kilocycles difficulties are encountered in measuring the current through the unknown impedances by the method of measuring the total current input to the bridge. If the meter question is eliminated, the actual loss in sensitivity, which is the only other objectionable feature of this admittance, may be made of no serious consequence up to frequencies as high as 2000 kilocycles. In all other respects, the shielding functions as satisfactorily at this frequency as at the lower frequencies.

Auxiliary Equipment. While auxiliary apparatus such as oscillators and detectors is not strictly speaking measuring apparatus, its operation is essential to the satisfactory operation of the measuring circuit and so a few words may be added regarding the shielding of this apparatus.

Provided they are separated sufficiently from the

7. J. G. Ferguson, "Measurement of Inductance by the Shielded Owen Bridge," *Bell Sys. Tech. J.*, July, 1927, pp. 375-386.

measuring circuit and from each other, there is no need to shield the oscillator or detector from the standpoint of operation of the measuring circuit. However, for maximum flexibility, it is desirable that they be so constructed that no special precautions are necessary in placing them relative to the measuring circuit. If, as is usually done, the individual apparatus included in these circuits is adequately shielded it is only necessary to place the completed equipment in an electrostatic shield to avoid all coupling to the measuring circuit or from one to the other. This is usually done by mounting the apparatus on a metal panel and placing it in a wood box with a sheet metal lining. By this means it is possible to place the auxiliary apparatus as close to the measuring circuit as desired, without introducing errors.

So far as the internal shielding of the auxiliary apparatus is concerned, the same rules as described for other apparatus hold. However, in the case of vacuum tube equipment, wherever any gain is introduced, coupling between parts of the circuit must be reduced in proportion to the gain introduced between these parts. This is usually accomplished quite readily by suitable mechanical design and may be insured by placing each stage in a separate grounded shield, although this is seldom necessary.

CONCLUSION

It has been impossible to go into very great detail in this brief paper on the subject of shielding. The attempt has been made, therefore, to outline a few general rules and to give representative examples of typical measuring circuits. It will be noted that the examples have been limited largely to the bridge circuit. This is because our experience has shown that this circuit is the most flexible and accurate over the whole of the frequency range over which precise impedance measurements have been made, and because the problems of shielding it are sufficiently difficult and varied to give satisfactory examples of the solution of rather complicated problems. The principles of shielding given have been found to apply equally well at all frequencies and it has been found that up to the maximum frequency at which precision measurements have been made, the shielding methods developed for use with moderate frequencies require practically no modification as the frequency is increased. Experience with measurements and measuring circuits up to 2000 kilocycles, makes it appear probable that when precision measurements are made at still higher frequencies, the shielded bridge circuit will continue to remain the most satisfactory measuring circuit.

Discussion

P. S. Bauer: In the ordinary network theory which we use in working out our bridge equations our fundamental assumption is that, in a series connection between any two points (conjugate or not) the current which flows is a function of time alone and not of position. We then define the electromotive-force

between those two points, neglecting mutual induction, as:

$$E = L \frac{di}{dt} + R i + \frac{1}{C} \int i dt$$

This implies the concept of lumped inductances, capacitances, and resistances.

If a bridge is to be used at frequencies of 2000 kilocycles, these lumped constants are non-existent with any degree of approximation. Consequently, it seems to me that it is meaningless to talk of either standards of these quantities at these high frequencies or to attempt to measure them by the application of our conventional definitions of these circuit parameters.

C. L. Dawes: I have one or two questions to ask Mr. Ferguson concerning the shielding methods which he describes. In his diagrams he shows shunted admittances from the resistances to ground. Obviously these admittances introduce errors both in the value of the resistances and in the current flowing through them. At low frequencies these errors may be negligible but at the higher frequencies they may be considerable. In developing bridges for high-voltage dielectric measurements we have found that such shunted admittances did not produce appreciable errors in capacitance measurements but even at 60 cycles they did introduce extremely large errors in the power and power-factor measurements. May I ask Mr. Ferguson the approximate magnitude of the errors which these admittances produce and to what frequencies it is possible to go before these admittances cause errors which are prohibitive.

J. G. Ferguson: Mr. Bauer made an interesting observation about the difficulty of separating electrostatic from electromagnetic effects. When we get down to practical measurements the first thing we find is that there are no such things as pure capacitances, pure resistances, or pure inductances, but that we have to make use of what we can get. The practical difficulty in shielding is that it is not correct theoretically to consider electrostatic shielding separately from electromagnetic shielding. It is possible to do this only where the conditions are defined to some extent.

I mentioned particularly that in this work, with the impedances we ordinarily use, electrostatic effects may be considered more or less separate from electromagnetic effects. However, as we go up in frequency the electromagnetic effects become more noticeable, and I might say as a practical instance that the bridge shown on Fig. 9, designed to go to about 3,000,000 cycles, requires that much consideration be given to electromagnetic effects as well as to electrostatic effects. Generally speaking we get into trouble when the current flowing in the electrostatic shield is sufficient to cause magnetic effects. This is definitely true in this bridge, and the only way that it can be taken care of is by using very great care to get a symmetrical arrangement and to keep the wiring in which the current from the shields flows, as short as possible.

Professor Dawes asked about the magnitude of the effect caused by the admittances across shielded resistors. This effect is a function of so many things that perhaps no general answer can be given. The dial box in Fig. 5, is practically a standard box except for the fact that it is shielded. The resistance goes up to a total of 10,000 ohms. The capacitance across each dial in this case is roughly $10 \mu\mu f.$, and the shielding adds about another 10. In other words the shielding reduces the maximum frequency to about half what it would be without shielding, for the same error in the impedance.

As far as the phase angle is concerned, the coils may be wound sufficiently inductive to compensate for the capacitance introduced by the shield. However, as we go up in frequency we get an error in the impedance which cannot be eliminated except by changing the method of construction.

It may be of interest to mention that in this box, having a capacitance of $10 \mu\mu f.$ without the shield, and an extra 10 with the shield, the error in the impedance of the 10,000-ohm setting

is about 0.5 per cent at 100 kilocycles and would be about 0.25 per cent if unshielded. As we decrease the resistance the error becomes less. If we increase the frequency above 100 kilocycles of course the error increases. However, there is a certain compensation there, since it is usually the case

that the higher the frequency, the lower the impedance used.

The bridge shown in Fig. 9 has resistances that go to a maximum of 1000 ohms. This allows us to go up to a much higher frequency with no greater error than in the box shown in Fig. 5, where the maximum resistance is 10,000 ohms.

Guarding and Shielding for Dielectric Loss^{*}

Measurement on Short Lengths of High-Tension Power Cable

BY E. H. SALTER¹

Associate, A. I. E. E.

Synopsis.—This paper presents the results of investigations made to explain the wide differences found between dielectric loss measurements made on full reel lengths of cable and on samples (10-ft. net length) removed from these reels. At least one source of such differences is found in losses occurring at the end of the cable,

these losses being insignificant in the case of the full reel but amounting to as much as 100 per cent of the loss in the normal sample. Methods of determining, controlling, and eliminating these end losses are described.

* * * * *

INTRODUCTION

WITH the advent of low loss insulations it has become necessary to make measurements of dielectric loss and power factor of power cables with greater accuracy and refinement. Since a large proportion of the measurements of this nature are made on comparatively short lengths of cable (10 ft. net length under sheath), the question has often been raised as to what influence the end conditions in these specimens might have on the results obtained.

GENERAL

At the Regional Meeting held in Pittsfield, Mass., May 25-28, 1927, Mr. C. L. Kasson presented a paper entitled *High-Voltage Measurements on Cables and Insulators*, in which he pointed out that in measurements with high continuous potentials and high single-phase alternating potentials very large errors might occur due to corona formation at the cable ends and on the lead wires. He showed how by complete electrostatic shielding and guarding of the sample under test and the instrument circuit these losses might be eliminated from the measurements.

Such shields and guards have been in use for some years past in laboratories making dielectric loss and power-factor measurements on short lengths of cable, where to accomplish this end it has been the practise to use the tank of the supply transformer as a shield for the transformer, to use lead-covered power cable for high-voltage leads wherever practicable, to screen the cable sample (and the air condenser, when used) and to use shields on all leads to the measuring instruments, these shields often surrounding the instruments as well. The proper use of such precautions eliminates practically all effects due to direct leakage (conductance leakage) and to capacitance connections between high- and low-voltage circuits. All of the above mentioned have to do chiefly with the equipment for making dielectric loss measurements. It is the purpose of this paper to discuss certain conditions relative to the

samples as such which have been found to play a large part in the results obtained in these measurements.

In test work, power cables fall into two general classifications, *i. e.*, single-conductor cable and multi-conductor cable. For power service most multi-conductor cable is three-conductor. There are then two general types of three-conductor cable, according to construction, *i. e.*, the belted type and the shielded conductor type. Each of these three groups represents a slightly different problem in preparation for test. They will be dealt with here in the order named.

GUARDING THE SINGLE-CONDUCTOR TEST SPECIMEN

Until recently the accepted scheme of guarding a single-conductor test specimen was as shown in Fig. 1.

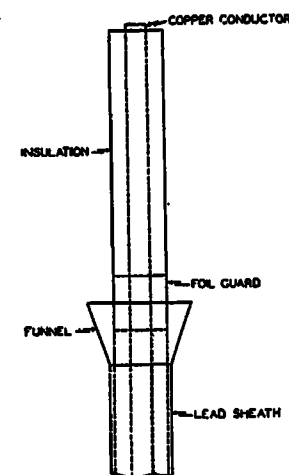


FIG. 1—PREPARATION OF CABLE ENDS FOR SINGLE-PHASE DIELECTRIC LOSS MEASUREMENTS

The guard consisted of a narrow band of foil, or wire, fastened over the insulation just above the end of the lead sheath. The purpose of such a guard is of course, first, to collect any direct surface leakage over the cable end, and second, to provide a terminus other than the lead sheath for the fringing electrostatic field at the cable end. There is little doubt that such a guard serves these purposes admirably.

However, there has been noted at times a tendency for tests on these short lengths of single-conductor cable to yield results much higher than that obtained on the reel length from which the specimens were removed, higher than could be explained by any reasonable lack of uniformity. The first indication of the possible cause of such high results was found in a cable which was removed from test after showing abnormally

^{*}Part four of a Symposium of six papers on Shielding in Electrical Measurements.

¹ Engineer, Cable Research, Electrical Testing Laboratories, New York, N. Y.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

high power factor and ionization factor. In an effort to locate the exact cause of the high values obtained, the lead sheath of this sample was slotted at 1-ft. intervals throughout its length, as shown in Fig. 2. Power factor and ionization factor determinations were then made on these individual sections. The result was that the high values obtained on the sample were definitely shown to be due to the extremely high power factor and high ionization factor of the end sections. To determine if this was a general condition,

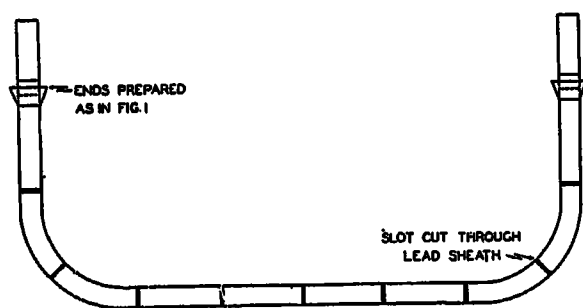


FIG. 2—DISTRIBUTION OF SECTIONS FOR POWER-FACTOR SURVEY ALONG NORMAL SAMPLE

a similar survey was made on a number of test samples with the same general result. The results obtained from a typical survey of this nature are shown graphically in Fig. 3, where each block represents the results of the tests on one 12-in. section. In each case, the

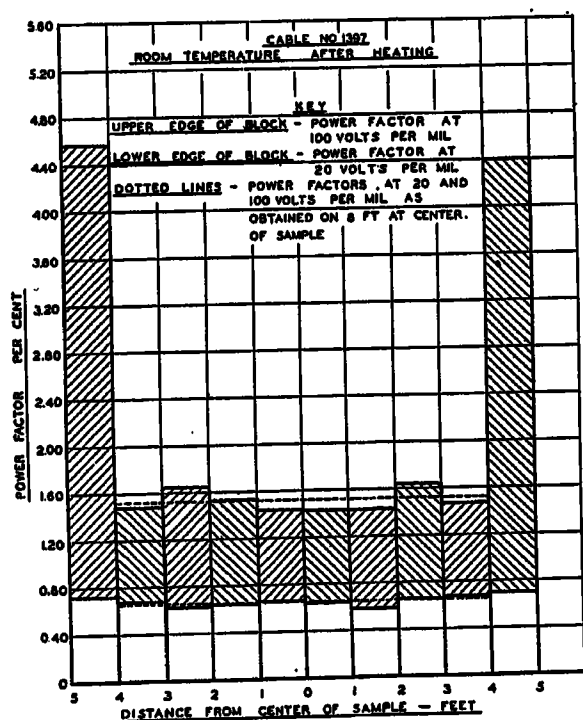


FIG. 3—SINGLE-PHASE DIELECTRIC LOSS MEASUREMENTS
Power-factor variation along length of cable

top of the block is the power factor at 100 volts per mil thickness of insulation while the bottom of the block is the power factor at 20 volts per mil. The height of the block is then the ionization factor.

These findings raised the question as to whether this condition existed before the heating cycle incident to the normal dielectric loss test. To answer this question a sample was prepared with the slotted sheath as shown in Fig. 2, but with each slot filled with insulation and sealed against loss of compound. A survey of this

sample before heating gave the results shown in Fig. 4. As the cable was heated it was found that the ionization factor of the end sections increased while that of the inner sections decreased, until at 98 deg. cent. the conditions were as shown in Fig. 5. Then as the cable was again cooled the ionization factor of the end sections remained high, while the inner sections returned to approximately the original condition before heating.

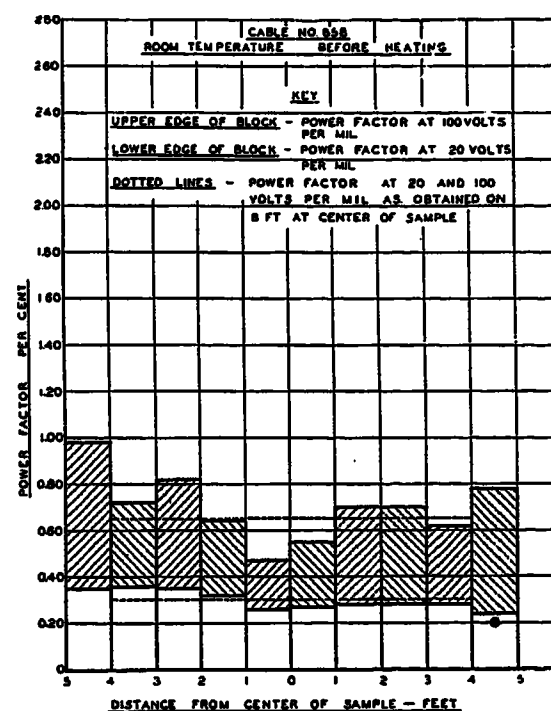


FIG. 4—SINGLE-PHASE DIELECTRIC LOSS MEASUREMENTS

Power-factor variation along length of cable

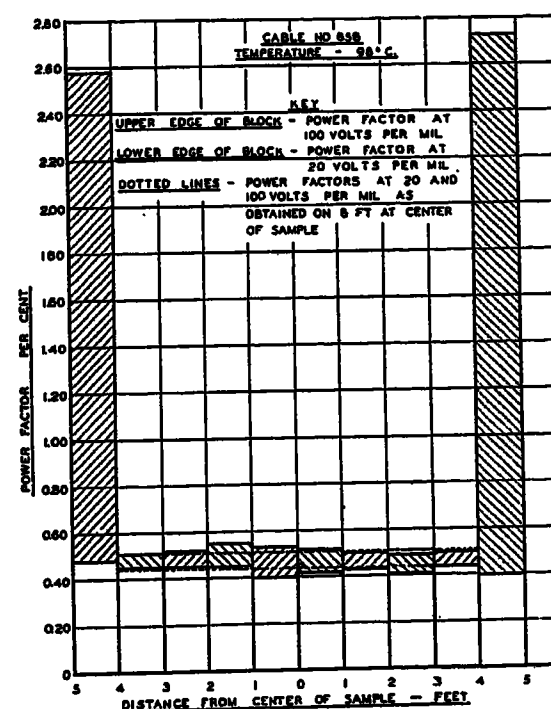


FIG. 5—SINGLE-PHASE DIELECTRIC LOSS MEASUREMENTS

Power-factor variation along length of cable

The final condition after cooling is shown in Fig. 6. These findings have since been confirmed by similar tests on other specimens.

It will be noted in examining Figs. 3, 4, 5, and 6 that for the 1-ft. sections at the ends of the specimens are for the most part the only ones showing any considerable change in power factor. In these end sections, the impregnating compound is to a certain extent open to the air so that the increases found are likely due to air

absorption with possible oxidation of the compound while at the higher test temperatures.

The method of eliminating these end losses from measurements on a length of cable is almost self-evident in an examination of the results shown, *i. e.*, eliminate these 1-ft. sections at the ends from the test circuit by making them a part of the guard or shield circuits.

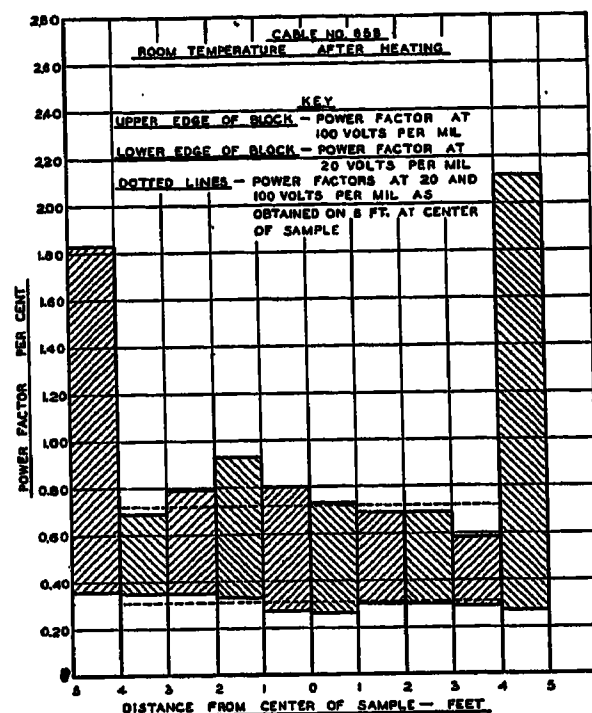


FIG. 6—SINGLE-PHASE DIELECTRIC LOSS MEASUREMENTS

Power-factor variation along length of cable

This, then, means that in preparing such a sample for dielectric loss tests circumferential slots are cut through the lead sheath at least 12 in. from each end. These slots are filled with insulation and sealed against loss

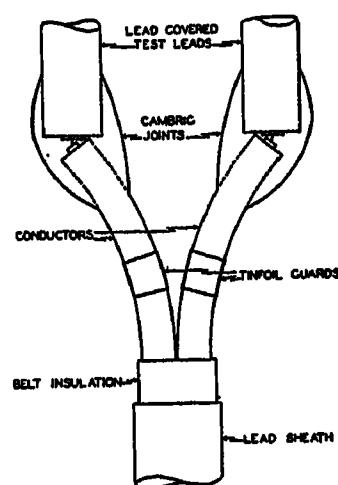


FIG. 7—A METHOD FOR TESTING CROTCH LOSSES

of oil when the cable is heated. The central section of lead sheath then forms the test electrode while the isolated sections at the ends are used as guards.

GUARDING THE BELTED THREE-CONDUCTOR TEST SPECIMEN

Dielectric loss tests may be made on three-conductor cable with either three-phase potential, obtaining the loss directly, or with single-phase potential, computing the loss from the results of a series of tests. While the tests described below were all made with three-phase

potential it is felt that the findings are equally applicable to tests made with single-phase potential.

The measurement of dielectric loss under three-phase potential is usually by means of the wattmeter using the three wattmeter method of measuring power in a four-wire three-phase circuit with the current coil of the wattmeter inserted between the ground or neutral

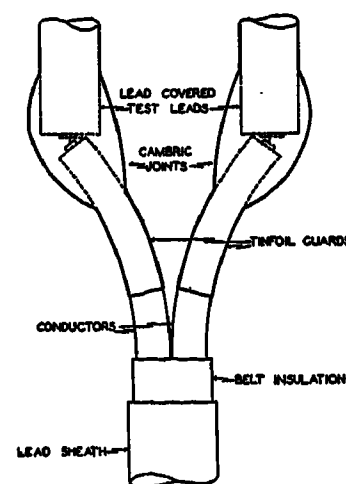


FIG. 8—A METHOD FOR TESTING CROTCH LOSSES

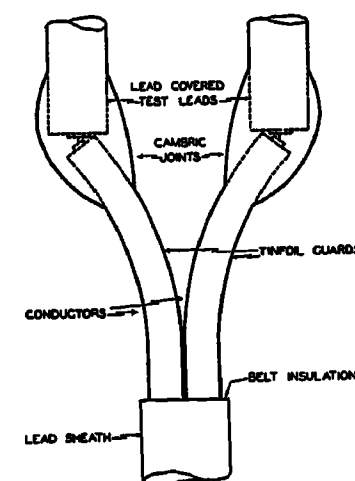


FIG. 9—A METHOD FOR TESTING CROTCH LOSSES

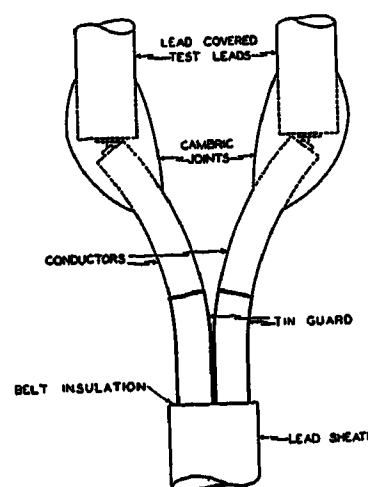


FIG. 10—A METHOD FOR TESTING CROTCH LOSSES

of the Y-connected system of transformers and the ground end of the transformer in the particular phase in which measurement is to be made. This means that *any* currents reaching ground return through the wattmeter. Hence, guard and shield circuits for each phase must be connected back to the ground end of the transformer in that particular phase if the currents to the guards are not to pass through the instrument. In

other words, three independent systems of guards and shields must be used, one for each phase.

This condition means that all shielding and guarding must be complete and must be phase-for-phase. It has therefore been the practise in making such measurements to use three single-phase supply transformers each mounted on insulators, each transformer completely shielded with wire netting and all high-voltage connections made with single-conductor lead-covered

(if two guard systems become connected the current coil of the wattmeter is shunted in those two phases). The presence or absence of such guards seemed to have little effect on the resulting loss measured.

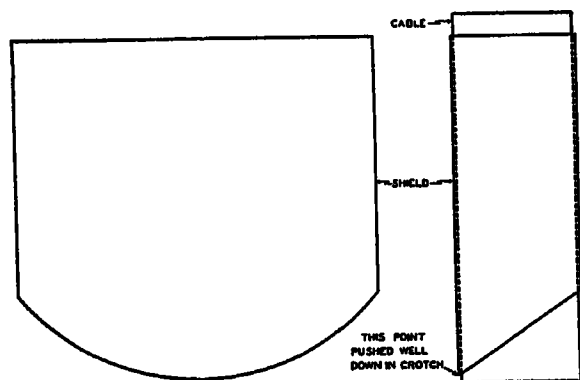


FIG. 11—SHAPE OF TIN-PLATE SHIELDS

cable with the lead sheath of each lead connected to the shield system for that particular phase. The specimen of cable under test is then arranged so that the ends of its conductors come very close to the ends of the lead cables, thus making the actual connectors not more

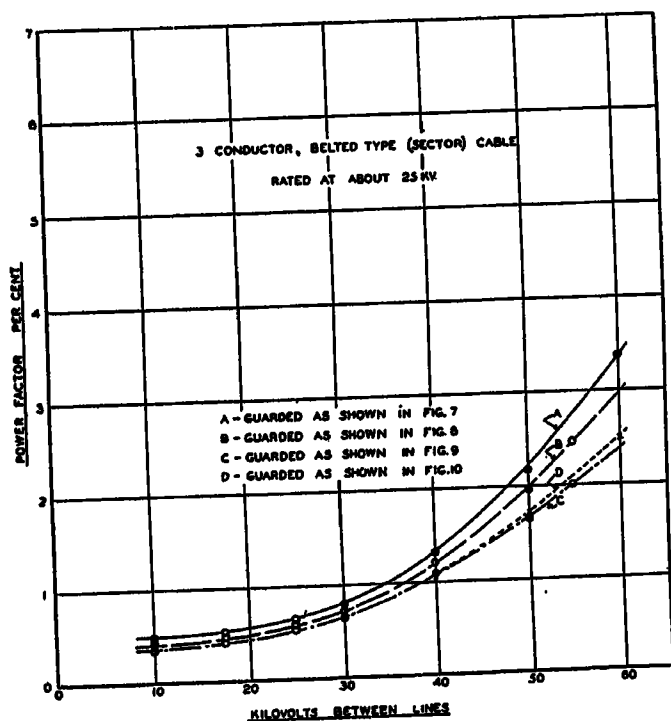


FIG. 12—VARIATIONS OF POWER FACTOR WITH VOLTAGE

than one inch in length. These connectors are then wrapped with black varnished cambric tape to make a smooth tight joint.

In making dielectric loss measurements on samples of belted three-conductor cable it was the practise to make the joints as described above and to apply tin-foil guards as shown in Fig. 7. The samples of cable were prepared in such a way that the belt insulation extended beyond the lead sheath about one inch. From this point the conductors were spread apart and the guards placed high enough on the individual conductors so that there was little danger of connection between them

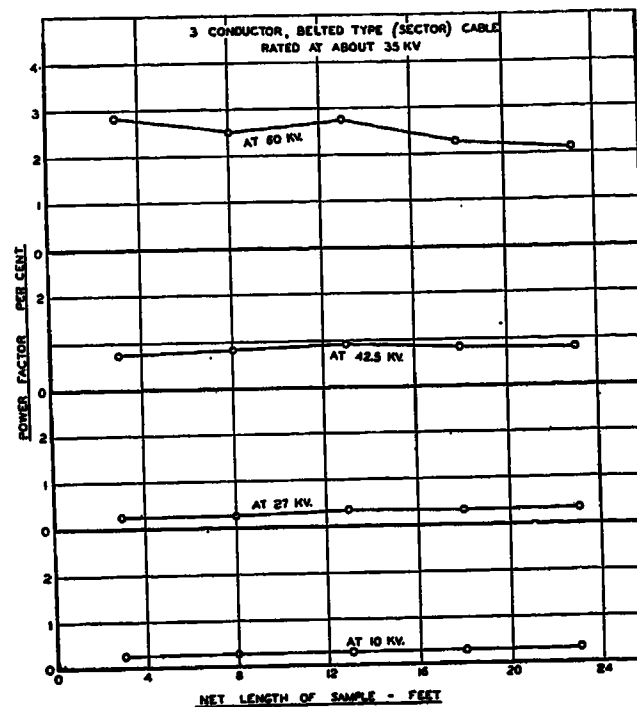


FIG. 13—VARIATION OF MEASURED THREE-PHASE POWER FACTOR WITH NET LENGTH OF SAMPLE

It is evident, however, that this scheme guards only against extraneous currents over the conductor insulation to the sheath and does not eliminate any of the currents which might flow through the capacitance between the various "exposed" conductors. This error has become increasingly significant, particularly in the case of the higher voltage cables where ionization of the

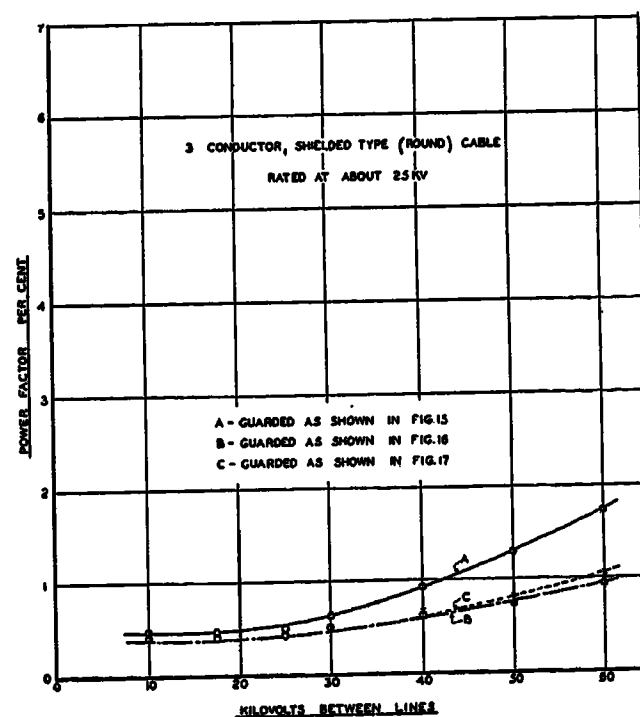


FIG. 14—VARIATION OF POWER FACTOR WITH VOLTAGE

air in the crotch of the cable gives visible signs of the loss in the form of corona.

In order to determine the magnitude of these end losses and to find the most effective method of preparing the ends of these samples in order to render these end losses negligible, a series of samples was prepared and

tested under each of the following conditions. The starting point was the normal sample prepared as described above and shown in Fig. 7. This guard system was then augmented by completely covering the cambric-wrapped joints over the connections to the test leads with tin-foil, thus completing the guarding from transformer to the old band guard (Fig. 8). After a set of measurements the belt insulation was cut back even with the end of the sheath and these guards

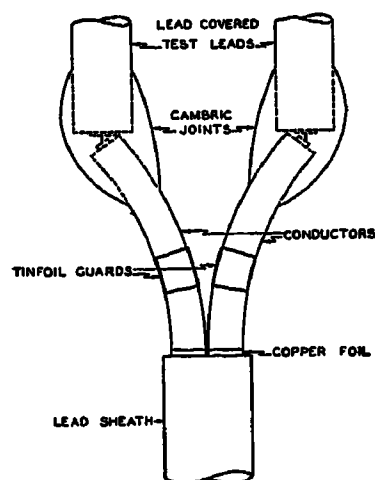


FIG. 15—A METHOD FOR TESTING CROTCH LOSSES

extended well down into the crotch (Fig. 9). Finally, all of these additional guards were removed with the exception of the four inches of guard well down in the crotch of the ends (Fig. 10). In order to get the guards well down into the crotch and yet keep them insulated, tin-plate cut as shown in Fig. 11 was formed around the conductors, covered with a layer of thin varnished

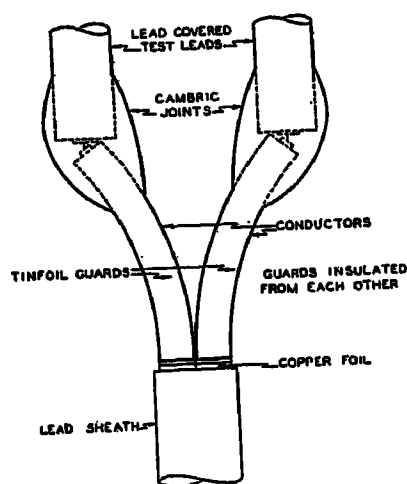


FIG. 16—A METHOD FOR TESTING CROTCH LOSSES

cambric, and driven down into the crotch. The results of a typical set of these tests are shown in Fig. 12.

A guarding scheme which eliminates end losses should give comparable results in measurements made on long and short lengths of cable. Accordingly, tests were made in which measurements were taken on 25-ft. lengths of cable and on the various sections as these lengths were reduced in 5-ft. decrements. This entire series of tests was made using the guarding scheme shown in Fig. 10, namely, guards about 4 in. long placed well down in the crotch and insulated from each other. Fig. 13 shows the results of a typical test of this kind.

In addition to the loss in the ends due to the tendency for corona formation between conductors in the three-conductor cable there is likely also an inherent loss of the type found in the single-conductor cable. At this time it does not appear possible to determine nor to eliminate this end condition from dielectric loss tests of three-conductor cables.

GUARDING THE SHIELDED THREE-CONDUCTOR TEST SPECIMEN

The problem of guarding the ends of the short specimen of shielded three-conductor cable is much the same as that of guarding the ends of the belted three-conductor cable. In both cases the problem is to prevent corona formation in the crotch and to reduce the loss between conductors. The studies of end conditions in the shielded conductor cable followed much the same lines as the studies of the belted cable. Due to the type of construction the crotch losses are much more readily controlled, however.

The results of a series of tests made on one of a

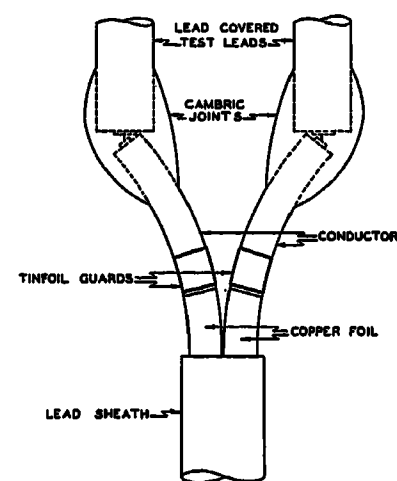


FIG. 17—A METHOD FOR TESTING CROTCH LOSSES

number of samples of shielded conductor cable tested are shown in Fig. 14. The end conditions for these various tests are illustrated in Figs. 15, 16, and 17. Fig. 15 shows the old method of guarding, in which only a band was put around each conductor while the metal-foil of the cable was cut off in the crotch. The completely guarded end is shown in Fig. 16, while Fig. 17 shows the final arrangement in which the metal-foil of the cable is cut off well above the crotch and the band guard placed just above. This arrangement was found to be practically as good as the complete guarding and much easier to accomplish.

CONCLUSIONS

The investigations of end losses in dielectric loss tests of short specimens of high-tension power cable appear to indicate that the most satisfactory methods of minimizing these end effects are to be found in the following methods of preparing the test ends.

1. Single-conductor cable is most effectively guarded against end losses by isolating about 12 in. of cable at

each end of the specimen for use as guards. When making temperature runs, the slots in the lead sheath incident to this preparation must be filled with insulation and sealed against oil leakage. The best slot width is approximately $\frac{1}{8}$ in., narrower slots being difficult to maintain and wider slots affecting the loss measurements due to the fringing field from the slot edges.

2. Three-conductor, belted type, cable is practically free from corona loss in the ends if the samples are prepared with the belt insulation cut off even with the sheath end and guards four to six inches long are placed well down in the crotch. For most effective placing of the guards it is advisable to make them of tin-plate or some similar stiff material which can be driven down into the crotch. A thin layer of varnished cambric placed over the guards before inserting serves to insulate them one from the other.

3. The simplest scheme of preventing crotch losses in the shielded three-conductor cable is to leave the metal-foil on the individual conductors beyond the crotch space, a matter of four to six inches. Narrow band guards placed above the ends of the metal-foil then take care of surface leakage.

Discussion

E. W. Davis: We are interested to see that Mr. Salter's experience with the crotch losses of three-conductor cable is in complete agreement with our experience. Data taken in our laboratory more than three years ago on 3-conductor belted cable showed that, as would be expected, filling the crotch with impregnating compound greatly decreased the ionization there and lowered the observed power factor two-thirds. Similar tests made with shields of different length showed continued decrease of power factor with increased shield length up to $7\frac{1}{2}$ in. but no further change in power factor beyond $7\frac{1}{2}$ in. shield length, indicating that there was no appreciable ionization at 100 volts per mil on this particular cable beyond $7\frac{1}{2}$ in. from the crotch.

Mr. Salter suggests that the ionization in the cable end-sections shown in Figs. 3, 5, and 6 is due to absorption of air and to oxidation of the compound. We have considerable test data indicating that in the particular conditions under consideration, neither effect should result in any increase of ionization factor. The slight excess of ionization in the end-sections of Fig. 4 is undoubtedly due to insulation loss beyond the end of the sheath that is not taken care of by the narrow guard ring, as shown by Mr. Salter. However, it is believed that the extreme end-section ionization shown in Figs. 3, 5, and 6 is also due principally to the same loss beyond the end of the sheath. When the cable is heated, the compound becomes thinner, and since there is nothing to restrain it beyond the end of the sheath, it drains away from that portion of the cable down into the cone, leaving voids behind in the insulation. The ionization of these voids greatly increases the loss beyond the end of the sheath and results in the extreme ionization of the end-sections shown in Figs. 3, 5, and 6.

In Figs. 3 and 6 a small part of the ionization of the end-sections, and a large part of the ionization of the inner-sections is due to expansion of the compound within the cable when heated and its consequent expulsion from the open end of the cable. Upon cooling again the greater part of this compound remains outside the cable, resulting in increased void space throughout the cable.

The decreased ionization of the inner-sections when at 98 deg.

cent (Fig. 5 compared with Fig. 4) is of course due to the expansion of the compound and consequent decrease of the void space.

A. S. Dana: I should like to ask Mr. Salter if with his scheme of guarding he is now able to duplicate the readings on a 10-ft. length that he obtains on factory lengths.

D. W. Roper: I was glad to have Dr. Silsbee enlarge upon the definition set forth by Dr. Curtis with reference to the term "shielding," as otherwise my discussion might have been excluded.

In Chicago we are making some tests at the present time to check a number of tests that have been proposed for predetermining the stability of the insulation of high-voltage cable. We are using for the test a size and type of cable in which this factor is of great importance, that is, 66 kv., single-conductor, 750,000 cir. mil with $\frac{1}{2}$ in. of impregnated-paper insulation. We are making the tests on samples of full-size cable, connecting in series several lengths made by different manufacturers, with insulating joints in the lead sheath so that the power factor of each section can be measured independently. The cable is subjected to heating and cooling cycles at about double normal voltage, and the cable is heated by means of current through the conductor applied by means of a current transformer insulated for the test voltage.

In making the tests for power factor and ionization factor, some difficulties are encountered that do not occur with a three-conductor cable; that is, with current on a single-conductor cable a voltage is induced in the sections of the lead sheath that must be neutralized or compensated for in some manner in order to avoid their effect on the measurements. The engineers working on this problem have devised a suitable method for eliminating the effect of this induced voltage, and it is hoped that they will later be able to present their methods to the Institute.

S. J. Rosch: This symposium brings to mind a problem which has baffled us for some time, and to which we hope that someone interested will offer a solution.

We have an insulation-resistance set, in which one side of the galvanometer is permanently connected to an independent solid ground. This ground is obtained by means of a No. 4 B&S solid copper wire fastened to a copper plate buried six feet under ground in moist soil. The dimensions of the plate are 1 ft. square by $\frac{1}{4}$ in. thickness.

In the same room, but located approximately 15 ft. away, is a single-phase transformer one of whose terminals is connected to an independent ground of similar construction.

Occasionally, when breaking down samples of high-tension cable, at the instant when cable failure occurs, a surge results which occasionally burns out the moving coil of the galvanometer. In view of the high impedance of the galvanometer, I wonder why this phenomenon occurs and what method of shielding is necessary to prevent such occurrence.

In discussing the measurements on the single-conductor cable, Mr. Salter, I believe, did not mention the method he used in making his measurements, whether it was a phase-defect method, a bridge method, or a dynamometer-wattmeter method. I should be interested to know whether Mr. Salter made any attempt to control the guard potentials in his circuit. In our new laboratory we intended to measure power factor and dielectric loss by means of the phase-defect method, three-phase. The apparatus is arranged so that measurements can be made three-phase as well as single-phase.

This symposium I believe would not be complete without some additional data as to whether it is necessary to control the guard potentials in the three-phase method, that is, using the dynamometer-wattmeter method, and I also believe that we should have comparative data of measurements made according to the bridge method described by Professor Dawes, with the various controls for guarding the potential, and the dynamometer-wattmeter

method with guard potentials unneutralized, to see just what the comparative results would be.

C. L. Dawes: I may be able to throw some light on the phenomenon described by Mr. Rosch. At one time we were running tests on a rubber-covered cable wound in a coil and immersed in a tank of water. The power for testing was obtained from a 25-cycle motor-generator set which derived its power from the 110-volt d-c. power mains supplied by the factory power plant. The lighting circuit in the room was supplied from 60-cycle service obtained from the local utility. Hence the two sources of power were entirely independent of each other. When the cable suddenly punctured the lights in the room suddenly went out and we found that the 10-ampere fuses had blown. We were as mystified as Mr. Rosch is by the effects which he observed. The only explanation at which we could arrive was that the fuses were blown by the electromagnetic disturbance created by the sudden rush of current at breakdown. The cable being in the form of a coil of several turns might possibly have been linked sufficiently close with the lighting circuit to permit sufficient transfer of energy to blow the fuses. I am merely offering this incident as a suggestion and not as the posi-

tive explanation of the not unlike phenomenon described by Mr. Rosch.

E. H. Salter: During the past two years we have been putting into practise the suggestions made in this paper, and over that period of time have found that, in general, the results obtained on a normal 10 ft. dielectric-loss sample have given very close check against the factory measurements on full reels, that is, against the ionization test as made in the factories on the full-reel lengths.

In connection with the single-conductor cable, Mr. Rosch has asked about the method used. All our single-phase measurements are made by the phase-defect compensation method. In that method the resistance thrown between either the test plate of the air condenser, or the test section of cable, and ground is of the order of 150 ohms. Working on a sample cable 10 ft. in length or less this will produce a maximum drop of about 0.5 volt. We have found that under these conditions, with the lead capacitance of the air condenser equal to the lead capacitance of the cable, the error due to failure to balance the guards amounts to less than 0.01 per cent, absolute value of power factor. In the average measurement this is negligible.

Precautions Against Stray Magnetic Fields in Measurements with Large Alternating Currents

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Synopsis.—In electric power stations, it is often necessary to make accurate measurements of current or power when the instruments are located near to the cables carrying large alternating currents. The magnetic field produced by these currents may constitute a serious source of error in the measurements unless careful precautions are taken to guard against such disturbing effects. This paper summarizes the various principles and methods for detecting

and minimizing the errors which may arise from this source. The principal methods are; (1) to so arrange the cables carrying the large currents that they produce as little stray magnetic effect as possible; (2) to use instruments of the shielded or of the astatic type; (3) to repeat readings with the instrument connections reversed; and (4) to avoid all loops in the connecting leads.

* * * * *

I. INTRODUCTION

IT often becomes necessary in the central station or the laboratory to make precise electrical measurements with apparatus which is unavoidably located near conductors which are carrying large alternating currents. The magnetic field produced by such currents may become a source of serious error in the measurements, either because of the direct effect of the magnetic field in adding a ponderomotive force to the moving element of the instrument used in the measurement, or because of the electromotive forces induced in the measuring circuits by the alternating magnetic field.

The magnitude of the effects to be expected may be appreciated if one considers that at a point one meter (39 in.) away from the center of a long straight conductor which is carrying 5000 amperes, the field is 10 gauss. Keinath¹ states that in a certain German aluminum factory, no place could be found where the magnetic field was less than 20 gauss. The normal working field strength of a typical electrodynamic switchboard wattmeter is about 40 gauss and hence, such an instrument, if unshielded and placed in such a field, might be in error by as much as 25 per cent. It must, of course, be borne in mind that the actual error resulting from a given stray field depends not only on the magnitude of the field but also on both the direction of the field with respect to the apparatus which it is affecting, and the relative time phase of the field with respect to the currents flowing in the apparatus. Fields which are not synchronous with the current in the measuring circuit usually cause no error, but may cause troublesome beat effects and may affect the permeability of the iron in transformers.

It is the purpose of this paper to summarize the various principles and methods which have been suggested for detecting or minimizing the errors which may arise from the presence of stray alternating fields. This

treatment, however, will be limited to those methods which are applicable in the range of frequencies used in power generation and distribution, though many of these are also applicable to audio- and even radio-frequency measurements.

The most important methods are (1) proper arrangement of the conductors carrying the large current, (2) proper choice and arrangement of measuring apparatus, (3) repetition of readings with reversed connections, and (4) proper location of connecting leads. These methods will be discussed in order. It should be emphasized that no one of them constitutes a panacea for all stray-field troubles but that the obtaining of correct results usually requires the judicious application of several of these principles.

II. ARRANGEMENT OF CURRENT-CARRYING PARTS

Whenever it is possible to do so, the conductors carrying the heavy currents should be so placed as to minimize the stray field which they produce. While exact computations of the field produced by various possible arrangements are both difficult and unnecessary, it is often desirable to obtain a rough estimate of such fields; for instance in judging the relative merits of two alternative conductor arrangements. Such estimates may be based on the following approximate relations.

The field at a point P , a considerable distance from a flat loop of cable, is roughly $H = 0.2 A I N / D^3$, where H is the field strength in gauss, $I N$ is the ampere-turns in the loop, A is the area of the loop in sq. cm. and D is the distance in cm. from the center of the loop to the point P . When the point P lies near the axis of the loop or in the plane of the loop, the direction of the magnetic field is parallel to the axis of the loop. At points which lie in other positions with respect to the loop, the direction of the field is of course quite different, but can be estimated by reference to a sketch of the lines of force around such a loop (e. g., Fig. XVIII in Maxwell Electricity and Magnetism, Vol. 2, 3rd edition).

The field caused by a long straight conductor carrying a current which returns at a great distance is $H = 0.2 I / D$ and obviously drops off much less rapidly with distance than that caused by a loop. The lines of force are everywhere perpendicular to the conductor

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1. For all references see end of paper.

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and to the line joining the point considered to the nearest point on the conductor.

Fortunately, however, the return circuit is usually not very distant. If two long straight conductors are at a distance g apart, the field H at a point P located at a considerable distance D (measured from a line midway between the conductors) is $H = 0.2 I g/D^2$. The magnitude of the field for a constant distance D is nearly independent of the location of P with respect to the plane containing the two conductors, although, as in the case of a loop, its direction varies greatly from point to point. Since the stray field is proportional to the spacing g it is very desirable to make this as small as possible. When the conductor section must be large, it is well to use thin strips or slabs placed close together. The effective spacing g is then approximately the distance between center-lines of the slabs and may be made much less than the width of the slabs or the diameter of a circular rod of the same conductance. This arrangement has the further advantage of minimizing the self-inductance of the circuit and hence lessens the reactive volt-ampere capacity of the apparatus required for supplying large currents for testing purposes. In the equipment recently installed at the Bureau of Standards for current transformer testing bars 20 in. by $\frac{1}{2}$ in. have been used.

From the point of view of minimizing stray fields the ideal construction for the heavy conductors is to use a pair of coaxial cylinders. Such a return circuit produces no magnetic field at points outside the outer tube, provided the current distribution is symmetrical about the common axis of the cylinders. While this form of construction has been used to some extent in shunts² and certain types of instrument,³ it tends to introduce considerable mechanical difficulty especially in arranging terminal connections.

It is not generally appreciated how closely the ideal concentric construction can be simulated by subdividing one conductor and placing its parts symmetrically around the other bar. If the return conductor consists of four wires connected in parallel placed 90 deg. apart around the central outgoing conductor and at a distance g from it, the field at a distance D from the central rod has the value $H = 0.2 I g^4/D^5$. The direction of the field is tangential at positions which are on lines drawn through the central rod and each of the returns and is also tangential but in the reversed sense at positions on lines making angles of 45 deg. with these axes. The direction of the field is radial at positions on lines making angles of 22.5 deg. with the axes. When D is as great as $10 g$ the stray field with this arrangement is only one one-thousandth as great as that caused by an ordinary two-wire circuit with the same spacing.

Even the use of only two return conductors, each carrying one-half of the current and located one on each side of the outgoing conductor, gives a fairly complete neutralization of the stray field. With this arrangement, the field is $H = 0.2 I g^2/D^3$ where g is the distance

from the central conductor to either return. At a distance equal to $10 g$ the field is only one-tenth as great as that from a circuit which has a single return conductor at the same spacing. Here again the intensity of the field is independent of the orientation of the circuit.

The foregoing approximations apply to the case of a single-phase circuit only. When the currents causing the stray field are polyphase, the computations become more intricate. The two conductor arrangements most often used are those in which the three conductors carrying balanced three-phase currents are placed one above the other in a vertical plane, and those in which the conductors lie at the corners of an equilateral triangle. In the former case, the resultant stray field at a considerable distance is approximately $H = 0.2 \sqrt{3} I g/D^2$, where g is the spacing between adjacent conductors and D is the distance to the central conductor. The stray field has a time-phase in quadrature with that of the current in the central conductor, and the direction of the field at any point depends on the location of that point. The field is horizontal at points in the plane of the conductors and also at points in a plane through the central conductor perpendicular to this plane. The field is vertical (*i. e.*, parallel to the plane containing the conductors) at points in a plane which passes through the central conductor at an angle of 45 deg. to the plane containing the conductors.

If the three conductors lie at the corners of an equilateral triangle and carry balanced three-phase currents, the stray field at a distance has a magnitude given by $H = 0.1 \sqrt{3} I g/D^2$. It is purely a rotating field of constant magnitude, and its direction makes a complete revolution about an axis parallel to the conductors during each cycle of current. There is therefore a distinct difference between this type of field and those previously considered. In the previous cases even when the field is intense there is no electromotive force induced in an exploring coil if the latter is placed so that its plane lies along the direction of the lines of force, and this desirable condition is not disturbed as the coil is rotated about this direction as an axis.

In the case of the rotating field, there will be an e. m. f. induced in such a coil unless its axis is strictly parallel to that of the conductors. When in any other position a turning of the coil about an axis which is parallel to the conductors will merely change the phase of this e. m. f. without changing its magnitude.

Table I summarizes the formulas given in the preceding paragraphs and indicates by the numerical values computed for a typical case the magnitude of the stray field to be expected.

An unshielded electrodynamic wattmeter can be used to detect and measure stray magnetic fields by applying rated voltage to the moving coil circuit while the current circuit is left open. When the orientation of the instrument and the phase of the applied voltage have been adjusted to give a maximum deflection, this deflec-

TABLE I

Effective value of stray magnetic field in gaussses at a distance of D cm. from the axis of symmetry of a group of long straight conductors carrying a current of 10,000 amperes and arranged as indicated in column 1, with the spacing between adjacent conductors 10 cm.

Arrangement	Formula	Stray field			
		$D = 50$	$D = 100$	$D = 200$	$D = 500$
Single conductor, return at great distance	$\frac{0.2 I}{D}$	40	20	10	4
Return at distance g . . .	$\frac{0.2 I g}{D^2}$	8	2	0.5	0.08
Return in two wires on opposite sides	$\frac{0.2 I g^2}{D^3}$	1.6	0.2	0.025	0.0006
Return in four wires at corners of square	$\frac{0.2 I g^4}{D^4}$	0.064	0.002	0.000625	0.0000064
Return in coaxial cylinder		0	0	0	0
Three-phase circuit conductors in a plane	$\frac{2 \sqrt{3} g I}{10 D^2}$	13.8	3.5	0.87	0.138
Three-phase circuit conductors in a triangle	$\frac{\sqrt{3} g I}{10 D^2}$	6.9	1.73	0.43	0.069

tion is proportional to the stray field present at the point where the wattmeter is located. The instrument may be calibrated by placing it at the center of a loop of large radius (R centimeters) carrying a known current (I amperes) in phase with the voltage applied to the wattmeter. The field (H in gaussses) at the

center of such a loop is $H = \frac{2 \pi N I}{10 R}$ where N is the number of turns in the loop.

III. CHOICE OF MEASURING APPARATUS

The second line of procedure in avoiding stray-field errors is the proper choice of type and arrangement of measuring apparatus.

When it is feasible, use should be made of magnetically shielded instruments. In these instruments the windings are enclosed in a thick shield of high-permeability iron, which serves to greatly reduce the intensity of the stray field in the interior of the instrument. The protection thus afforded varies of course with the nature of the instrument and the design of the shield. A more detailed discussion of such magnetic shielding will be found in the papers of Curtis* and Gokhale.† The literature^{4,5,6} contains data showing a reduction of the stray field errors by factors which vary from 1/3 to 1/60 in different cases. As is often the case with any type of shielding, there is always the danger that the presence of the iron shield may somewhat affect the action of the instrument, and it is customary to laminate such shields so as to minimize the eddy currents which would otherwise be produced by the

field from the instrument windings themselves. There is also a possibility of the shield acquiring a certain permanent magnetization which may affect the operation of the instrument on direct current. This effect can be eliminated, however, by taking the mean of readings with the currents direct and reversed.

The operating torque of many electrical instruments is the result of the interaction of two magnetic fields, one of which is much stronger than the other. This is the case, for example, in a separately-excited electro-dynamometer or in a vibration galvanometer. In such types of instrument it is desirable to design the instrument so that the moving element of the instrument is the one which produces the weaker of the two magnetic fields. The ponderomotive force on the moving element resulting from its reaction with the stray field (which is of course fixed in space) is thereby made less than with the converse arrangement. Thus an electrodynamic instrument should be used with the separate excitation applied to the fixed coils; and a vibration galvanometer of the fixed-magnet moving-coil type should be preferred to a moving-magnet instrument, unless, of course, some additional shielding is used with the latter.

Certain types of apparatus, such as electrodynamic instruments and mutual inductors, can be built in astatic form by using duplicate coils wound in opposite directions whose effects are additive as regards the currents to be measured but subtractive as regards stray field effects. Apparatus of this type is very much less subject to stray field errors than is ordinary non-astatic equipment, and should be used whenever possible. However, it is well to bear in mind that astatic construction does not entirely eliminate all possibility of stray-field error. The two coils of an astatic instrument seldom have exactly the same area turns, and even if the construction is perfect, the compensation is complete only if the stray field is uniform in direction and intensity throughout the space occupied by the instrument. The field around a laboratory or power station is usually far from uniform, and may be materially different at the two coils of an astatic instrument. Thus, if an astatic mutual inductor the coils of which are 20 cm. apart is used two meters away from a current-carrying loop of wire, the e. m. fs. induced in the two coils will be in the ratio of 1 to 1.37 and the effect of the astatic construction will be to reduce the stray-field error to 1/6 of the value which would occur with a single-coil inductor.

The standard resistors or shunts which are sometimes used in measuring heavy alternating currents must also be considered as liable to stray-field errors. It is usually necessary to place such resistors rather close to the heavy current circuit and the leads running to the current terminals of the shunt are an ever-present source of stray field. Fortunately, most of the modifications in construction which tend to reduce the self-inductance of the shunt also reduce its susceptibility

*See p. 1263.

†See p. 1307.

to stray fields. It frequently happens that the use of additional sets of potential leads distributed symmetrically around the axis of the shunt and all connected in parallel will materially reduce the stray-field error without affecting the self-inductance.

Electrostatic instruments are entirely free from error resulting from stray magnetic fields, unless the moving element contains a very large amount of magnetic impurity. Thermocouple type instruments are affected only to the extent that the permanent magnet of the d-c. millivoltmeter may be partially demagnetized by an extremely strong stray field. Hot-wire instruments, especially those designed with several parallel current paths for measuring large currents, may be seriously in error if a stray field tends to change the distribution of the current among the branch circuits.

IV. REVERSAL OF CONNECTIONS

A further method, which is almost always applicable even in cases where the circumstances have not allowed the experimenter any leeway in the arrangement of either the current-carrying conductors or the measuring apparatus, is to make two sets of measurements between which the connections of part or all of the apparatus have been reversed. The most desirable procedure is first to make such changes in connections as will reverse the direction of all currents in the measuring circuits except the heavy currents which are suspected of producing a stray field. This may usually be done by reversing the secondary connections of the current transformers. If the results of the repeat measurement made after this reversal show only a slight difference from the original results, one-half this difference may be taken as a measure of the stray field error and the mean of the two results may be considered to be correct. If the difference is large, it indicates the need for locating and removing the source of error. The same principle may then be applied further by studying each piece of apparatus separately and taking a pair of readings before and after reversing its connections. In most cases it is of course necessary to reverse two pairs of terminals, as, for instance, the primary and secondary circuits of a mutual inductor or transformer, or the fixed and moving coil circuits of an electrodynamic instrument. After a survey of this nature has shown which parts of the network are introducing the errors, these parts should be so moved or modified as to reduce the error to a reasonably small value. A final pair of readings should then be taken to give the correct mean value.

While this principle of reversed connections is much more effective than those previously discussed as a means of eliminating stray field errors, even this principle should not be trusted too far. If the difference in readings obtained with direct and reversed connections is large, it follows that some parts of the equipment such as the moving coils of the instruments, the second-

dary coils of an adjustable mutual inductor, etc., will be differently placed in the stray field when the two readings are made. Consequently, the stray-field effects will not be exactly opposite in the two cases, and the mean will not be the true value. Care must also be taken in the case of instruments with non-uniform scale law to make sure that the proper mean (which may not always be the arithmetic mean of the readings) is taken. Thus, for example, if current is being read on an electrodynamic ammeter having a square-law scale, the arithmetic mean of the two readings of current observed with the direct and reversed connections in the presence of a synchronous stray field will not be exactly the true value of the current. The true value is given by the current corresponding to the average of the two angular deflections or, to express it differently, by the square root of the mean of the squares of the two current readings. This differs from the arithmetic mean of the currents by an amount which is one-sixteenth of the square of the ratio of the difference in the two current readings to the mean current. These differences are fortunately almost always negligible.

V. CONNECTIONS TO CURRENT CIRCUIT

The coupling between the measurement circuit and that carrying the large currents is usually made through a current transformer. There is, unfortunately, a dearth of experimental data on the effect of stray magnetic fields on the ratio and phase angle of current transformers.⁷ One would expect, however, that the effect would not be greater in magnitude than the differences observed when the primary conductor is placed in different positions with respect to a hole-type current transformer.⁸ With most transformers these differences amount to only a few parts in ten thousand in ratio, but with certain unfavorable combinations of construction and conditions of use, may be as great as one-half per cent.

It occasionally happens that the coupling between the measuring circuit and the heavy-current circuit must be made by a direct connection of potential leads, so as to measure the impedance drop in a run of bus or across some piece of apparatus carrying the large current. In such cases, it is important to recognize clearly that the impedance drop may be very different from the resistance drop and to place the potential leads so that the resultant e.m.f. at the measuring instrument may approximate as closely as possible to the desired quantity. If the total impedance drop is desired, the potential leads should be brought off separately at right angles to the heavy conductor, in such a direction as to avoid as far as possible the magnetic effect of other parts of the heavy current circuit. In other words the mutual inductance between the potential leads and the current circuit

should be zero. On the other hand, if the resistance drop only is desired, a potential lead should be laid back tightly against the conductor throughout the span from its point of attachment to that of the other potential lead. From the point where the two leads meet they should be kept close together and preferably twisted throughout the run from the conductor to the instrument. The theoretically perfect condition is to place the potential leads so that they are linked with a magnetic flux of the same amount as that which links the main conductor. In the case of round conductors this would require the impracticable condition that the lead lie in a hole or groove inside the current carrying rod. In the case of thin rectangular bars, however, the requirement can be met by placing the potential lead close to the bar at a distance from the center of its long side equal to 0.3 of the total width of the bar.

The precaution of twisting the two leads of each part of the measuring circuit is of course essential in all parts of any set-up when stray magnetic fields are present and is a most effective way of avoiding stray e. m. fs. in the leads. Yet an appreciable induced electromotive force has at times been observed in a carefully twisted pair of potential leads when the twisted pair was lying at right angles across a pair of heavy cables (also twisted) which were carrying 1000 amperes. In these cases, the change of field strength with distance was so abrupt that the adjacent loop of the twisted lead could not compensate for the large e. m. f. induced in the loop which lay closest to the heavy cable.

In cases when the conductor arrangement is such that the potential leads cannot be placed in the desired location, it is often possible to correct the experimental results by computing the various mutual inductances involved. Formulas are available⁹ for such computations for a great variety of shapes and arrangements of conductors.

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Discussion

C. T. Weller: In regard to Dr. Silsbee's paper, I hope he intends to include in his printed discussion the photographs of his current-transformer testing equipment which he showed here. I was glad to notice that one of schemes for testing high-current transformers represents the one under which they are generally used; namely, with a single return circuit nearby. However, under this condition the shielding effect is largely eliminated in that part of the circuit.

If I understand him correctly, he is planning to use a standard current transformer with series-multiple connections to cover the higher currents; this constitutes an indirect scheme somewhat similar to the one he is now using for the higher-voltage potential transformers. I desire to emphasize that equipment is now available for determining the respective transformer accuracies directly over a wide range of current and potential values.

S. L. Gokhale: With reference to the use of astatic wound coils, Dr. Silsbee says: "The two coils of an astatic instrument seldom have exactly the same area turns and even if the construction is perfect, the compensation is complete only if the stray field is uniform . . ."

The first of the above two points needs only a brief comment even if the two coils be not exactly equal to start with, they can be easily tested and readjusted to any limit of accuracy which may be required. Such a system may therefore be looked upon as a completely satisfactory solution of the problem of uniform stray field. Let us call such a system, an "astatic system of the first order;" it is represented by the formula, $(+1, -1)$ which explains itself.

But even if the stray field be not uniform, exact compensation may still be obtained by the use of astatic systems of higher order. Imagine a system of three coils, represented by the formula $(+1, -1, +1)$; this means that the first and the third coils of the system are of equal area-turns wound in the same direction and that the middle coil is wound in the opposite direction with area turns double of each of the end coils. Such a coil system can exactly compensate for a non-uniform field of the second degree, that is a field having a uniform rate of variation from point to point in any direction. A non-uniform field of third degree can be compensated for by the use of a coil system of the third order $(+1, -3, +3, -1)$; a field of the fourth degree by a system $(+1, -4, +6, -4, +1)$ and so on.

The several coils of the systems of different orders can be expressed by the general formula, $(+1, -1)^n$ expanded by the binomial theorem. These astatic systems are analogous to the harmonic magnets of the corresponding orders described in Section 6 of my paper in this symposium. In our practise we had thus far only one occasion to use a system of the third order; a system of the second order $(+1, -2, +1)$ is quite satisfactory for most purposes.

F. B. Silsbee: Mr. Weller asked some questions in connection with the current-transformer testing equipment which are rather remote from the shielding problem. The answer is that when we have a single return, (one of the four return leads only in use), then, of course, we do not get the compensating effect; the field varies inversely as the square of the distance and more stray field is present in the room. We hope when the set-up is working we shall not get much difference in transformer performance between one and four leads and that we shall be able to use all four leads in our regular testing.

In reference to his other question, we do feel at the Bureau that there is a good possibility in the use of standard transformers which are standardized with their coils so connected as to give a lower range, and then used so as to give a higher range. We have pushed this matter in voltage transformers to a range of 100 kv.

We are intending to pursue the same policy in the case of the current transformer.

We recognize there is one serious source of difficulty in the contact resistances of the various circuits which are connected in parallel. We feel, however, that by using an exploring coil which can be moved opposite each of the primary turns in succession, we shall be able to tell whether or not the current is dividing

properly between the turns, and thus at least know that something is wrong if anything is wrong. We hope the matter will work out satisfactorily.

I think Mr. Gokhale has added quite a bit to the theory of astatic coils by generalizing the process. I think there might be cases where this method would be applicable, but generally it would be rather a complicated thing to carry out.

Magnetic Shielding

(Shielding of Magnetic Instruments From Steady Stray Fields)

BY S. L. GOKHALE¹

Member, A. I. E. E.

Synopsis.—This paper is a brief survey of the vast amount of work on magnetic shielding of instruments against steady stray fields, and allied problems, by several authors during the last fifty years. It contains, first, a simplified presentation of the method of zonal harmonic analysis, by way of introduction to the mathematical theory of shielding as presented by those authors, and second, a brief summary of their theoretical inferences and experimental findings. In a paper of this kind no "conclusion" is necessary; the following table of contents explains the plan of presentation followed herein.

1. Introduction
2. Designed and incidental shielding
3. Problem of shield design
4. Theory of shielding, methods of analysis
5. Method of magnetic images (geometric)

6. Harmonic analysis; conception of harmonic magnets and harmonic images
7. Zonal harmonics
8. DuBois' formula for shield factor
9. Material for shield
10. Importance of differential permeability for shielding
11. Failure of magnetic shield
12. Incidental shielding
13. Dynamic shielding
14. Differential shielding
- Appendix
- Mathematical theory of Zonal Harmonics
15. Zonal Harmonic coefficients
16. Geometric and harmonic images
17. Analysis of any magnetic field in general into component spherical or zonal harmonics.

1. INTRODUCTION

THE phenomenon of magnetic shielding is very important from the practical as well as from the theoretical point of view. A considerable amount of work has been done in the past, by way of developing a complete mathematical theory for each important case of shielding which occurs in laboratory or engineering practise. Several formulas have been evolved for practical use, and some of them have been verified by test. The mathematical treatment of the subject as presented by the several authors is not only not very easy to follow, but it starts out from a point in higher mathematics generally beyond the range of studies of the average technical student. Consequently, most of the work in the past has remained like a sealed book to all except those who were compelled, and had the ability, to forge their way through that mathematical maze. The purpose of this paper is two-fold, first, to introduce the mathematical aspect of the problem in a simple form so as to bring the reader to the starting point of the classical work presented by authorities like Professor Rucker, without having to go through the Laplacian equation and its solution as a necessary preparation, and second to summarize results of the mathematical study and of the experimental findings of the other physicists. It contains nothing new except the mode of presentation.

2. DESIGNED AND INCIDENTAL SHIELDING

For practical purposes the study of shielding may be divided into two divisions.

Part 6 of a Symposium of six papers in Shielding in Electrical Measurements.

1. Research Engineer for Magnetism, General Electric Company, Schenectady, N. Y.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

(a) Study of shield design

(b) Study of incidental shielding

The classification is important for practical purposes only, and has no foundation in theory. The purpose of the study (a) is to obtain a formula for the most efficient shield and is concerned with those cases wherein good shielding is essential; the study (b) is concerned with cases in which shielding occurs incidentally as a collateral phenomenon irrespective of desirability or undesirability of the effect. The same fundamental theory underlies both the above aspects of the study, but the conditions involved in the two problems call for different methods of approaching the solution, hence the need of the above classification. The problem of designing a satisfactory shield for protection of galvanometers against external fields belongs to the first class, the problem of computing magnetic forces on a conductor located in the slots or tunnels of the armature of a motor belongs to the second class. The solution of the first problem is best obtained by the use of harmonic analysis, the solution of the second by the use of electromagnetic images (geometric). In anticipation of the following analysis, it may be noted at this point, that the method of harmonic analysis is also fundamentally a method of magnetic images. (Section 6).

3. PROBLEM OF SHIELD DESIGN

The problem of shield design in its theoretical aspect is the problem of formulating an equation expressing the ratio of the original field at a point, to the field at the same point when protected by the shield. In other words, the problem consists of deriving an equation of the form.

$$H_e = H_i \cdot F(\mu, a, b, c, \text{etc.}) \quad (1)$$

$$= g \cdot H_i \quad (1-2)$$

where

H_e , is the field without protection

H_i , the field with protection

g , the shield factor

μ , the permeability of the shield material

a, b, c , etc., geometric characteristics of the shield

In the case of spherical or cylindrical shields the symbols a, b, c , stand for the several radii of the shells which form the shield.

In practise, the problem goes one step farther, and calls for an expression for the most efficient shield design, together with the value of the shield factor of that design. For convenience of computation, the shields are supposed to consist of one or more concentric shells of spherical or cylindrical form. The permeance function of a cylindrical shield—see Equations (10) and (15); that is, of a shield made of a set of cylindrical shells of sufficient length, is only 8/9 of that for a spherical shield of corresponding radii and of the same material. See Equation (17). It is obvious from this that shells of intermediate form must have a shield factor somewhere between these two extreme limits, and it is therefore not necessary to try to compute for or to design any other shapes. Theoretically, the cylindrical shield is supposed to be of infinite length but it has been found in practise that for a point near its center, a shield of length equal to its diameter is almost as good as one of infinite length, and a shield longer than its diameter by any amount gives an efficiently shielded space of that length. (DuBois, "Magnetic Shielding," *Electrician*, Vol. 4, p. 645, Fig. 9). A small amount of further improvement can be obtained by the use of shield plates at both ends for which no formula has been worked out, (Dye, *Journal of Scientific Instruments*, Vol. 3, p. 69). Small holes in these plates make practically no difference in the efficiency of the shield. It is understood that in the case of the cylindrical shield, the axis of the shield should be at right angles to the magnetic field against which protection is required. In all cases, shielding depends on the permeability of the shield; the higher the permeability of the shield material the more efficient the shield will be. (See also Section 10.)

4. THEORY OF SHIELDING: METHODS OF ANALYSIS

Theoretically, the action of a shield consists of a change of path of flux lines due to refraction of those lines at the boundary surfaces of the shield caused by differences of permeability on the two sides of the boundary. This interpretation of the shielding process cannot be reduced to mathematical formulas, except in an indirect way in terms of some intermediate phenomenon, such as distribution of magnetism on the surfaces of the shield. Thus there arise three practical methods of interpreting the action of the shield in mathematical terms.

1. The method of least reluctance
2. The method of images
3. The method of harmonic analysis

The first method lends itself easily to account for the action of the shield in a qualitative sense, but it is not convenient for quantitative work. The second and third methods are best suited for computation. The first method is based on the conception that lines of flux are refracted so as to follow the path of least reluctance, and consequently, that most of the flux lines follow the apparently longer but really the easier curved path through the walls of the shell, instead of traversing the straight and shorter path through the space enclosed by the shield. This line of reasoning is very convenient for a classroom exposition but it fails to explain clearly the fact that some lines traverse the space enclosed by the shell instead of all lines going around the enclosure; nor does this conception explain the bending of the lines outside the shield where they approach the shield without touching it, and follow a longer path of apparently greater reluctance without

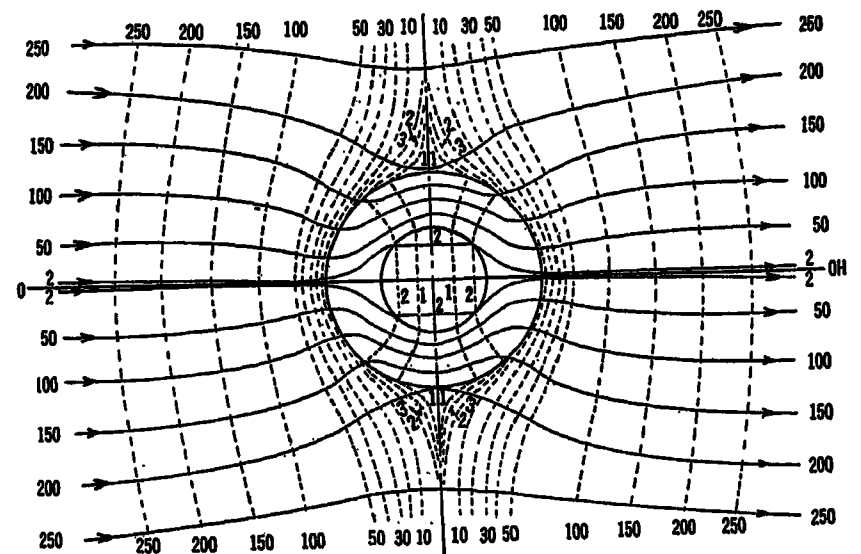


FIG. 1—BENDING OF FLUX LINES BY A SHIELD

any compensating diminution of reluctance by going a part of the way through the iron (see Fig. 1, Line No. 200). It is possible to explain all these difficulties by taking fully into account the diminution of permeability by congestion of flux, the bending of the equi-potential surfaces, and the broadening of the tubes of flux, but then the explanation is no longer simple and has no other compensating merit. The other two methods are based on the conception that the shells are themselves magnetized by the inductive action of the field and become in turn a source of a second magnetic force which in the enclosed space is opposed to the original field. The value of the field in this space is the resultant of the original field and the opposing field produced by the shield. This method of interpretation is not very difficult to comprehend and has the further merit of lending itself easily to mathematical analysis.

5. METHOD OF MAGNETIC IMAGES (GEOMETRIC)

This method is analogous to the well known method of electrostatic images. The magnetism induced by the original field on the surfaces of the shield is regarded as equivalent to certain imaginary magnetic poles located

at appropriate points just as in the case of electrostatic images. The resultant field is then easily computed in accordance with Coulomb's law of inverse square. In the case of solid spheres, solid cylinders, and infinite mass bounded on one side by a plane surface, the images can be easily located and the computation presents no difficulty, but when the problem involves more than one surface the magnetic distribution can be represented only by a series of infinite images which adds greatly to the difficulties of their location and computation. This method is therefore not available for problems of shield designs which even in the simplest case involve two sur-

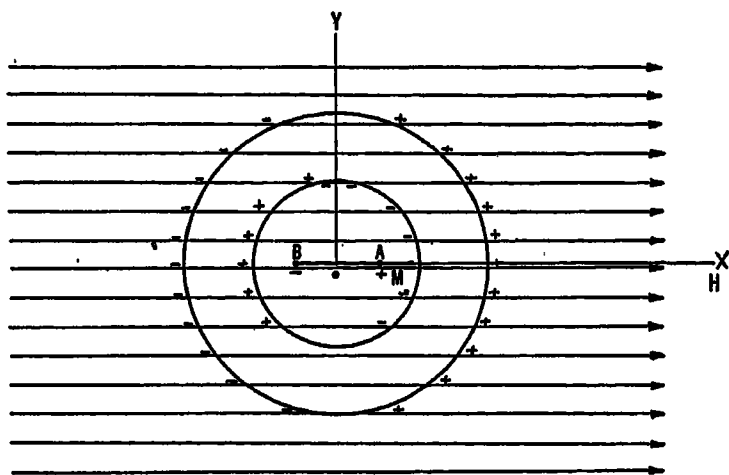


FIG. 2—MAGNETIC POLES ON A SHIELD DUE TO INDUCTION (BENDING OF LINES IS IGNORED IN THIS DIAGRAM)

faces and in most practical cases at least four surfaces. This method of images will be referred to as a method of geometric images, to distinguish it from the method of harmonic images which will be described next.

6. HARMONIC ANALYSIS: CONCEPTION OF HARMONIC MAGNETS AND HARMONIC IMAGES

The method of zonal harmonics is fundamentally a method of images, with this difference, that with the method of images proper, that is, of geometric images as defined in the last section, both the magnitude and location of the images are determinate and are determined directly from the magnetic and geometric conditions of the problem. In the case of zonal harmonics, the images are indeterminate in location as well as in magnitude to start with, but they can be located at any point selected at will; the magnitudes of the images can then be determined by a process analogous to that of determining the coefficients in a Fourier series.

The images in this method of analysis consist of a series of sets of imaginary magnets of small size, arranged as required by the conditions of the problem, so as to produce at any point on any specified spherical surface, the same magnetic potential as the magnetic distribution in question produces. This will be clear from the following explanation.

In Fig. 2 let H be the magnetic field in question which may or may not be uniform. A spherical shield is placed in the field, the center of the sphere being the origin of the coordinate axis. The field induces magnetic poles on the surfaces of the shield as indicated

qualitatively by the diagram. The lines of flux in the field and also within the walls of the shell, are also bent under the influence of the induced magnetism (Fig. 1), although this bending is ignored in Fig. 2 for simplicity. The magnetism induced on the shield, which is analytically the basic reason for the changes in the field, can be represented by equivalent magnetic images, all located near the center of the sphere, and of magnetic strengths which can be determined analytically.

Imagine a very short magnet of polar strength m , of length $2a_1$, and of magnetic moment $M = m \cdot 2a_1$, located at the center of the sphere and oriented positively, along the axis of X , that is with the positive pole on the positive side of the coordinate axis. (See Fig. 3-1.) We will call this magnet a harmonic magnet of the first order, and of strength M_1 . If $M_1 = 1$, the magnet is called a unit harmonic magnet of the first order.

Next, imagine two shorter magnets of length $2a_2$ each, one located about the positive pole of the first magnet M_1 and oriented positively, the other located about the negative pole of M_1 and oriented negatively. (See Fig. 3-2.) Call this system of magnets, a harmonic magnet of the second order, of strength $M_2 = m \cdot 2a_2 \cdot 2a_1$, where m is the strength of each of the four poles. If $M_2 = 1$, it becomes a unit harmonic magnet of the second order.

Next, imagine a system of four still shorter magnets of length $2a_3$ each located about the four poles of M_2 and oriented positively or negatively according to the poles of M_2 concerned. (See Fig. 3-3.) Call this system of magnets, a harmonic magnet of the third order, of

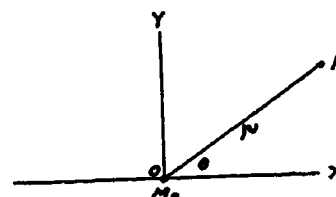


FIG. 3-0

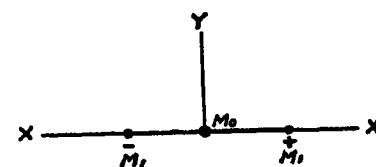


FIG. 3-1

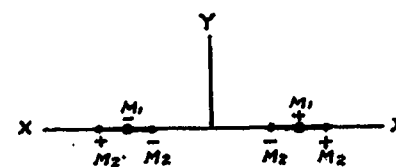


FIG. 3-2

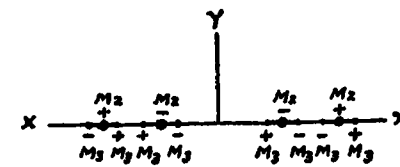


FIG. 3-3

FIG. 3—HARMONIC MAGNETS; THE SUBNUMBER REFERS TO THE ORDER OF THE MAGNET

strength $M_3 = m \cdot 2a_3 \cdot 2a_2 \cdot 2a_1$, where m is the strength of each of the eight poles. If $M_3 = 1$, it becomes a unit harmonic magnet of the third order.

Repeat the process, doubling the number of magnets of each step: thus we have harmonic magnets of successively higher order. The strength of the magnet of n th order is $M_n = m \cdot 2a_n \cdot 2a_{n-1} \cdot \dots \cdot 2a_2 \cdot 2a_1$. If $M_n = 1$, we have a unit harmonic magnet of the n th order.

The process can also be carried backwards one step: imagine a single positive pole $M_0 = +m$ located at the

center of the sphere, and therefore at the middle point of M_1 , (see Fig. 3-0, 3-1). Call this single pole magnet, a harmonic magnet of zero order of strength M_0 .

The backward process can be carried indefinitely beyond the zero order, giving imaginary harmonic magnets of negative orders, M_{-0} , M_{-1} , M_{-2} , etc. These magnets give rise to zonal harmonics of second kind, viz., Q_0 , Q_1 , Q_2 , etc. This paper is limited to the study of real harmonic magnets and their effects.

This is the planetary conception of harmonic magnets.

For analytical purposes, the harmonic magnets can also be conceived as the result of magnetic displacements, as follows:

Imagine a single positive pole $+m$ located at 0, (Fig. 3-0), and call this as before a harmonic magnet of zero order, of strength $M_0 = +m$.

Imagine a second pole $-m$, superposed on $+m$ so as to neutralize both to start with; the two poles are then stretched apart over a very short distance $dx = 2a_1$ along the coordinate axis X , the pole $+m$ moving in the direction $+X$. Thus we obtain a harmonic magnet of the first order, of strength $+M_1 = m \cdot 2a_1$.

Next, imagine an exactly similar magnet with its poles reversed, and superposed on the first; the two magnets are now slid along each other, so as to displace the corresponding poles over a distance of $2a_2$. This gives us a harmonic magnet of the second order. And so on.

The planetary conception is easier to comprehend, but the displacement conception is better adapted for analytical operation. See Section 15, Eq. (21).

The method of zonal harmonics is based on the *theorem*,³ that any magnetic distribution, symmetrical with respect to an axis, can be represented as the aggregate effect of a series of magnetic images, in the form of harmonic magnets of different orders and of appropriate strengths, all located about any selected point, and oriented along the axis of symmetry. The *theorem of harmonic analysis*, in general is,⁴ that any distribution of magnetism can be represented by a series of harmonic magnets, all located about any point arbi-

3. The conception of harmonic magnets is due to Maxwell who first applied it to the study of electrostatic fields. Maxwell's conception was limited to real harmonic magnets.

4. The theory of spherical harmonics in general, is not limited either to symmetry or to uniformity of the field or to symmetry of distribution of the induced magnetism. By the use of three sets of harmonic magnets along the axis of X , Y , and Z , respectively, any distribution and any kind of field can be analyzed into harmonics, but for simplicity of presentation this paper deals with the simplest case, namely, that of a symmetrical distribution.

The first of the above two enunciations of the theorem refers to the problem in its limited scope, the second refers to the problem in its general aspect. When all the imaginary harmonic magnets lie along a single coordinate axis, they give rise to zonal harmonics (see Section 7). When they are distributed along the three axes they give rise to spherical surface harmonics in general. Zonal harmonic analysis is only a simpler particular case of spherical harmonic analysis.

trarily selected somewhere not necessarily near the center of the distribution and of magnitudes capable of being determined by a process analogous to that of Fourier's Series. For a more precise and formal statement see Equation (6).

7. ZONAL HARMONICS

The potential at any point on the surface of a sphere, due to a harmonic magnet of any order located about the center of the sphere, is called a simple spherical harmonic of the corresponding order. In the particular case of a sphere of unit radius, and with a harmonic magnet of unit strength, the value of the potential reduces to a much simpler form; it is then called a zonal harmonic coefficient of the corresponding order. (See discussion following Eq. (29).)

Let TAT' (see Fig. 4), be the meridian section of a

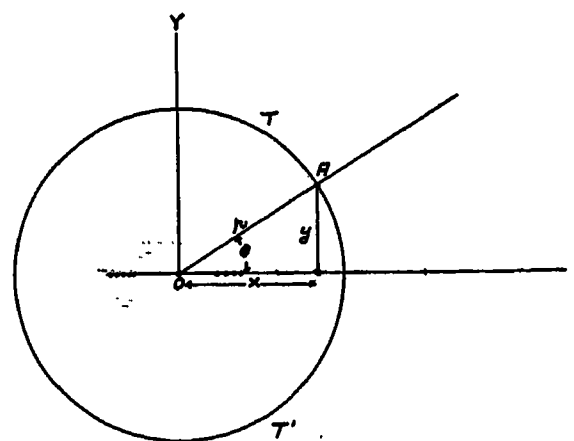


FIG. 4

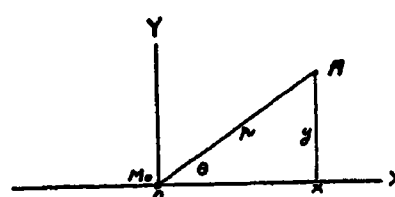


FIG. 4-0

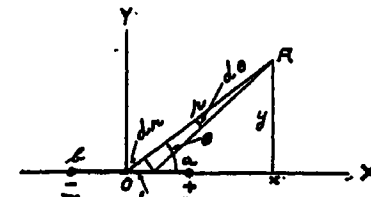


FIG. 4-1

FIG. 4—POTENTIAL AT A POINT DUE TO HARMONIC MAGNETS; SUBNUMBERS REFER TO ORDER OF MAGNET

sphere of radius r , and with center O , which is also the origin of the coordinate axes. Let A be any point on the sphere arbitrarily selected, having coordinates x and y , or the corresponding polar coordinates r and θ . Let the harmonic magnet under consideration be located about the center and oriented along the prime vector. Then the potential at A due to such a magnet of any order n and of strength M_n can be expressed by the general form.

$$V_n = M_n \cdot \frac{1}{r^{(n+1)}} \cdot f_n(\cos \theta) \quad (2)$$

The expression on the right hand side is a simple spherical harmonic of the n th order. The factor $f_n(\cos \theta)$ is called a zonal harmonic coefficient of the corresponding order.

The specific values of the potential at A due to harmonic

magnets of orders ranging from 0 to 7, and of strengths M_0, M_1, M_2 , etc., are

$$V_0 = M_0 \cdot \frac{1}{r} \quad (2-0)$$

$$V_1 = M_1 \cdot \frac{1}{r^2} \cos \theta \quad (2-1)$$

$$V_2 = M_2 \cdot \frac{1}{r^3} \cdot (3 \cos^3 \theta - 1) \quad (2-2)$$

$$V_3 = M_3 \cdot \frac{1}{r^4} \cdot 3 (5 \cos^3 \theta - 3 \cos \theta) \quad (2-3)$$

$$V_4 = M_4 \cdot \frac{1}{r^5} \cdot 3 (35 \cos^4 \theta - 30 \cos^2 \theta + 3) \quad (2-4)$$

$$V_5 = M_5 \cdot \frac{1}{r^6} \cdot 15 (63 \cos^5 \theta - 70 \cos^3 \theta + 15 \cos \theta) \quad (2-5)$$

$$V_6 = M_6 \cdot \frac{1}{r^7} \cdot 45 (231 \cos^6 \theta - 315 \cos^4 \theta + 105 \cos^2 \theta - 5) \quad (2-6)$$

$$V_7 = M_7 \cdot \frac{1}{r^8} \cdot 315 (429 \cos^7 \theta - 693 \cos^5 \theta + 315 \cos^3 \theta - 35 \cos \theta) \quad (2-7)$$

For detailed computation and derivation of the above equations, see Appendix, Section 15.

The several values of V for the different harmonic magnets, are simple spherical harmonics, each of the order corresponding to that of the harmonic magnets. Each of these harmonics is made up of four factors, namely

The factor representing the strength of the magnet
The r -function factor, a negative rational power of r
The θ -function factor, a rational function of $\cos \theta$

The numerical factor, which is merely a part of the θ function factor; it is separated merely for convenience, the separation having no theoretical significance.

The θ -function factor together with the numerical factor is called a zonal harmonic coefficient. It represents the value of V for a sphere of unit radius, with a harmonic magnet of unit strength at the center. Using the symbol Z to represent that coefficient, the general equation for V (Equation (2)) may be expressed in the form

$$V = M_n \cdot \frac{1}{r^{(n+1)}} \cdot (Z_n) \quad (3)$$

where Z_n stands for $f_n(\cos \theta)$, (see Equation (2)).

In practise, the coefficient (Z_n) is divided by another numerical factor $n!$ (factorial n); it is then called "practical zonal harmonic coefficient" or briefly, zonal

harmonic, and is represented by the symbol P_n . Thus we have the equations

$$V_n = \frac{M_n}{r^{(n+1)}} \cdot (Z_n) \quad (3)$$

$$\text{or} \quad V_n = n! \cdot \frac{M_n}{r^{(n+1)}} \cdot P_n \quad (4)$$

$$\text{where} \quad P_n = Z_n/n! \quad (5)$$

(See Appendix, discussion following Equation (29).)

The theorem stated at the end of Section 6, may now be restated in more precise terms

The potential V at any point on the surface of a sphere, due to magnetic distribution symmetrical with respect to an axis, can be analytically represented by a series of the form

$$V = A_0 + A_1 \cdot r \cdot P_1 + A_2 \cdot r^2 \cdot P_2 + \text{etc.} \\ + \frac{B_0}{r} + \frac{B_1 P_1}{r^2} + \frac{B_2 P_2}{r^3} + \text{etc.} \quad (6)$$

where, A_0, A_1 , etc., and B_0, B_1 , etc. are determinate constants; sometimes only the first part ($A_0 + \text{etc.}$),

sometimes only the second part ($\frac{B_0}{r} + \text{etc.}$), and

sometimes both the parts are necessary according to the nature of the distribution which calls for analysis; stated in general terms, the series takes the form

$$V = \sum A_n r^n P_n + \sum \frac{B_n}{r^{(n+1)}} \cdot P_n \quad (7)$$

This is the basic equation underlying the method of zonal harmonic analysis in general, and of the analysis as applied to the problem of magnetic shielding in particular; for example, it is the starting point of Rucker's analysis in his classical article on shielding, wherein he has made use of this equation to derive his general formula for shield factor. (*Phil. Mag.* 1894, Vol. 37, p. 97). It may be noted that the above equation bears a close resemblance to Fourier's series in which we have

$$V = \sum (A_n \cos n \theta) + \sum (B_n \sin n \theta) \quad (8)$$

The resemblance is more than superficial, it can be shown that the zonal series is merely a more complex form of the Fourier series. The method of determining the values of the factors A_n and B_n in the case of the zonal series is exactly the same as in the Fourier's series.

Note: For significance of the constants A_n and B_n in Equation (7), see Equations (31-2), and (33-2); for proof of the theorem see Section 17.

8. DUBOIS' FORMULA FOR SHIELD FACTOR

It is not possible in a brief paper of this kind to go through the complete analysis of the shield problem. The purpose of this paper is merely to introduce the subject for the benefit of those whose knowledge of harmonic analysis is limited to Fourier's Series. For a more complete study of the problems, see "Magnetic

Shielding" by Esmarch (*Ann. der Physik*, Vol. 39, 1912, p. 1553), and by Rucker (*Philosophical Mag.*, Vol. 37, 1894-95, p. 95).

From Rucker's general formula referred to above, Dubois⁵ has derived the following formula for the case of a spherical shield of two concentric shells, with a shell of non-magnetic material between, (see Fig. 5).

$$g = 1 + \frac{2}{9} \frac{(\mu - 1)^2}{\mu} \left[(1 - p_1 p_2) + \left(\frac{(2\mu^2 + 5\mu + 2)}{9\mu} \right) m_1 m_2 m_{12} \right] \quad (9)$$

where

$$\begin{aligned} p_1 &= r_1^3/R_1^3; & m_1 &= 1 - p_1 \\ p_2 &= r_2^3/R_2^3; & m_2 &= 1 - p_2 \\ p_{12} &= R_1^3/r_2^3; & m_{12} &= 1 - p_{12} \\ g &= H e/H i; & & \text{(see Equation (1-2))} \end{aligned}$$

Using the abbreviation symbol

$$c = \frac{2}{9} \frac{(\mu - 1)^2}{\mu} \quad (10)$$

where c is the permeance function of a shield of spherical form, the equation takes the form

$$g = 1 + c(1 - p_1 p_2) + c(c + 1)m_1 m_2 m_{12} \quad (9-2)$$

By making $r_2 = R_2$, and therefore, $p_2 = 1$ and $m_2 = 0$,

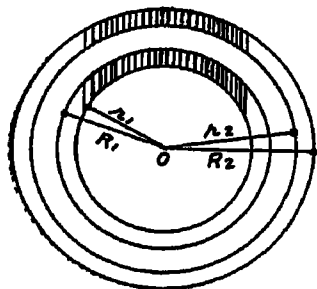


FIG. 5—SPHERICAL SHIELD OF TWO SHELLS

the outer magnetic shell is eliminated, and the shield is reduced to a single shell for which the shield factor is

$$g_1 = 1 + c(1 - p_1) \quad (11)$$

$$= 1 + c m_1 \quad (11-2)$$

$$\text{or} \quad (g_1 - 1) = c m_1 \quad (12)$$

$(g - 1)$ is called the shielding power of a shield.

Equation (11-2) shows that the shield factor of a shield depends not on the absolute size of a shield, but on m , that is, on the relative mass of the shell wall to the size of the shell.

In the same way by making $R_1 = r_1$ and therefore $P_1 = 1$, $m_1 = 0$, we have

$$g_2 = 1 + c m_2 \quad (10-2)$$

Dubois' equation may now be transformed so as to express g as a function of g_1 and g_2 .

$$\begin{aligned} g &= 1 + c(1 - p_1 p_2) + c(c + 1)m_1 m_2 m_{12} \\ &= 1 + c[1 - (1 - m_1)(1 - m_2)] + c(c + 1)m_1 m_2 m_{12} \\ &= (1 + c m_1)(1 + c m_2) - m_1 m_2 (c^2 + c) + c(c + 1)m_1 m_2 m_{12} \\ &= g_1 g_2 + m_1 m_2 (c^2 + c)(1 - m_{12}) \\ &= g_1 g_2 - c(c + 1)m_1 m_2 m_{12} \end{aligned} \quad (13)$$

5. See DuBois: *Electrician*, Vol. 40, 1897, p. 317.

This is DuBois' equation second form. This equation shows that the shield factor consists of two terms; the first of these is made of two main factors, each of these factors being the shield factor of the corresponding shell. The second or negative term represents the effect of the mutual reaction of the two shells on each other and is a measure of the loss of shielding power due to such reaction. For a pair of shells of given radial ratios (m_1 and m_2 constant), the reaction reaches the maximum value, and that g reaches the lowest value when $p_{12} = 1$, that is, when the air space is eliminated.

If the shells be not very thin, and also if the permeability of the shell material, and therefore the permeance function of the shield be very high, we can assume $c = c + 1$, and also $c m_1 = 1 + c m_1$, and $c m_2 = 1 + c m_2$ approximately; this approximation reduces DuBois' equation to a much simpler and more instructive form.

$$\begin{aligned} g &= (1 + c m_1)(1 + c m_2) - c(c + 1)m_1 m_2 p_{12} \\ &= c m_1 c m_2 - c^2 m_1 m_2 p_{12} \text{ (approximately)} \\ &= g_1 g_2 - g_1 g_2 p_{12} \text{ (approximately)} \\ &= g_1 g_2 (1 - p_{12}) \text{ (approximately)} \\ &= g_1 g_2 m_{12} \text{ (approximately)} \end{aligned} \quad (13-2)$$

That is, the shield factor of the whole shield is approximately the product of the shield factors of the individual shells multiplied by the clearance ratio of the air space between the shells. This form of the equation brings out clearly the function of the air space in improving the efficacy of the shield; it reveals the fact, not obvious at first sight, that a shield made up of two shells with non-magnetic space between is superior to a shield of the same size with all the space filled with the magnetic material. It would appear that the reluctance of a single shell filling the whole space occupied by the shield, ought to be less than that of a multi-shelled shield with air spaces between. This view is contradicted by the well recognized fact that a multi-shelled shield with air spaces between, is far superior to a solid shield of the same size, although the latter contains much more magnetic material and has apparently much less reluctance. DuBois' formula has been found to be in close agreement with the shield factor obtained by measurement. (DuBois, *Electrician*, Vol. 40, p. 653). In the case of cylindrical shields, the shield factor is given by a similar set of equations:

$$\begin{aligned} g &= 1 + \frac{1}{4} \frac{(\mu - 1)^2}{\mu} \left[(1 - q_1 q_2) + \frac{(\mu + 1)^2}{4\mu} n_1 n_2 n_{12} \right] \end{aligned} \quad (14)$$

where

$$\begin{aligned} q_1 &= (r_1/R_1)^2 & n_1 &= 1 - q_1 \\ q_2 &= (r_2/R_2)^2 & n_2 &= 1 - q_2 \\ q_{12} &= (R_1/r_1)^2 & n_{12} &= 1 - q_{12} \end{aligned}$$

Using as before the notation

$$d = \frac{(\mu - 1)^2}{4\mu} \quad (15)$$

the equation takes the simpler form,

$$g = (1 + d n_1) (1 + d n_2) - (d^2 + d) n_1 n_2 q_{12} \\ = g_1 g_2 - (d^2 + d) n_1 n_2 q_{12} \quad (16)$$

$$= g_1 g_2 n_{12} \text{ approximately} \quad (16-2)$$

This equation is analogous to that for spheres and leads to similar conclusions. For similar equations for shields of three shells see "Stalloy Ring Shields," by D. W. Dye. (*Journal of Scientific Instruments*, Vol. 3, p. 66, 1925.) Incidentally, it may be noted here that the ratio of the permeance functions in the two cases, *viz.*, spherical and cylindrical shells, is

$$\frac{c}{d} = \frac{2}{9} \frac{(\mu - 1)^2}{\mu} / \frac{1}{4} \frac{(\mu - 1)^2}{\mu} \\ \text{or} \quad \frac{c}{d} = \frac{8}{9} \quad (17)$$

Rucker has shown that for a shield of predetermined size, that is, when the innermost and outermost radii are specified, the most efficient shield is obtained when the successive radii of the shells form a geometric progression.

Equations for shields of more than three shells can be developed by further application of the same method, but the work involves a very laborious computation, and the improvement secured thereby is not great enough to justify the effort. A shield of three shells is quite satisfactory for almost all practical purposes, and one of the two shells is good enough for most of them. Equation (13-2) can be extended to any number of shells, as an approximate formula, if necessary.

9. MATERIAL FOR SHELLS

A reference to DuBois' formula shows that the shielding effect is nearly proportional to permeability; high permeability is therefore the most important requisite for shield material. In practise the fields against which protection is needed in galvanometer work, are generally very weak. The best material for a shield is therefore a material with high initial permeability. It is also necessary to remember that the material should be as free from hysteresis as possible. Material capable of developing strong local poles and retaining them, is worse than useless as it may create more disturbance than it can cure. Fortunately, material of high permeability has generally a very low hysteresis, which simplifies to that extent the problem of choice of material. The newly discovered alloys, permalloy and other alloys of that class, seem to be the best materials for shields but no recorded data on shield ratio for these materials are yet available. Professor Hill states that he has obtained a shield ratio $g = 1000$ by the use of a cylinder of sheet "Mu metal" rolled with a spacer of sheet copper, and with end plates of "Mu metal." (*Journal of*

Scientific Instruments, Vol. 3, 1925-26, p. 335.) For steady disturbing fields a massive material is just as good as laminated material but for disturbance of transient character massive material is at a disadvantage. The impulsive nature of the disturbance generates an eddy current, which chokes back a part of the flux and prevents it from going through the walls of the shell, thereby reducing the efficiency of the shell as is indicated by an impulsive kick of the protected galvanometer. Laminated shells have no disadvantage in particular. They are equally efficient against impulsive as well as steady disturbances. There seems to be some difference of opinion as to the mode of lamination. One method is to prepare a cylindrical shell by stacking a number of ring punchings of appropriate size; this scheme of lamination simplifies the problem of cutting observation windows in the shield. A second method is to prepare a cylindrical shell by rolling sheet material in the form of a cylinder. Theoretically, the latter type ought to be a trifle better, first because the shell acts like a system of multiple shells separated by non-magnetic shells, second because they contain no non-magnetic spaces parallel to the field for the external field to leak through, and third, because the formation of eddy currents tends to prevent the flux crossing the sheets, so as to force it to follow a path of least eddy along the walls of the shield. Practically no great improvement seems to have been observed. This may be due to the fact, that in rolling the sheet into a cylindrical shell its permeability is perhaps slightly impaired. This point deserves further testing.

10. IMPORTANCE OF DIFFERENTIAL PERMEABILITY FOR SHIELDING

In view of the facts that the shielding power of a shield depends on its permeability, and that the permeability of every known ferro-magnetic material depends on its flux density, having a maximum value when the material is carrying a certain amount of flux, attempts have been made to improve the shielding power of a shield by setting up a toroidal flux of sufficient strength to bring the material to the point of maximum permeability. It has been shown that this method of increasing permeability leads to no appreciable improvement in shielding power, (DuBois, *Electrician*, March 11, 1898, Vol. 40, p. 654). The cause of the failure of this method lies in the fact that the permeability on which the shielding power of the shield depends is not normal permeability B/H , but differential permeability $\Delta B/\Delta H$, where ΔH is the new increment of stray field, superposed on the previous field H , with corresponding values for ΔB and B . If the shield be in the non-magnetic condition to start with and be subjected to a toroidal magnetization up to the point of maximum permeability, and if a weak magnetic field be then turned on for the first time, the toroidal magnetization does give a slightly greater shielding power but a second application of the same field is attended by a reduced shielding power. In

every case after the first application of the stray field, the iron goes through a small unsymmetrical hysteresis loop the mean slope of the last side of the loop being the value of permeability, $\Delta B/\Delta H$, which determines the final distribution of the flux. Even in the case of the first application of the field the improvement is not very great, because the values of ΔH and ΔB are not both positive for the whole ring; in one-half of the ring the stray field is opposed to the flux and the corresponding permeability has the value not $+\Delta B/+\Delta H$, but the much lower value $-\Delta B/-\Delta H$. As the shielding power of the shield depends on the final distribution of the flux which in turn depends greatly on the differential permeability under the working conditions, it follows that DuBois' equation involving the normal permeability B/H , instead of $\Delta B/\Delta H$, is only a first approximation.

11. FAILURE OF THE SHIELD

In the ultimate analysis the operation of the shield, depends on the refraction of the flux lines as they pass through the successive surfaces of the shield. If therefore the lines of flux in any particular case are either strictly perpendicular or strictly parallel to the surfaces of the shield, there can be no refraction and therefore no shielding effect. For example, if one end of a long thin bar magnet is inserted inside a spherical shell all the lines emanating from the inserted pole will pierce through the shield and emerge as if there were no shield. If on the contrary a magnet were inserted inside the shell with both poles inside, the space outside will be almost fully protected by the shell. Only a few lines in the direction joining the poles will be perpendicular to the surfaces of the shell and will emerge outside unchanged; these will be a very small fraction of the total lines emanating from each pole of the magnet. As an example of parallel flux, we may consider the case of a tubular shield with a single wire carrying the current along the axis of the shield. The magnetic field at any point outside of the shield will be just as intense with the shield as without it. These cases of failure do not generally occur in practise, but it was necessary to mention them just for the sake of a correct theoretical understanding of the nature of the phenomenon.

12. INCIDENTAL SHIELDING

Imagine a wire carrying a current held in front of a plane face block of iron of infinite extent on the opposite side and of infinite permeability. The problem is to determine the form of the field and the distribution of magnetism on the surface of the block. A problem of this kind is easily solved by the method of electromagnetic images. Imagine the block removed for a time and another wire carrying a current of the same magnitude and direction located where the image of the first wire would have been formed if the face of the block had been a mirror. Such a current would be an electromagnetic image of the first current; the field at any point in front of the block can be obtained by computing the field produced

by the two wires separately and obtaining the resultant effect. For a point immediately near the block, the field would be perpendicular to the face of the block, the magnetic surface density at any point of the face can be computed from Coulomb's Law.

$$\sigma = H/4\pi \quad (18)$$

where H is the field at that point as computed by the image method.

This is the method of magnetic images. For more important cases occurring in engineering practise see Searle ("Magnetic Field Near a Cylinder of Iron," *Electrician*, Vol. 40, 1898, p. 453).

13. DYNAMIC SHIELDING

Imagine a wire carrying a current held in a magnetic field and at right angles to the field. The wire would be subject to a side-way pull proportional to the product of the field strength and the strength of the current. Imagine now a tubular magnetic shield surrounding the wire but not touching it. The field inside of the shield will be very much weaker and the side-way pull on the wire will be reduced in proportion. Suppose now that the shield is mechanically fixed to the wire so that the wire and shield must move together or not at all. The pull on the wire is now as strong with the shield as without it. This apparently paradoxical result is due to the fact that when the shield moves with the wire the lines of flux crossing the space inside the shield move in the opposite direction at a rapid rate, with a velocity inversely proportional to the weakening of the field. Therefore, the rate at which the lines are cut by the wire is now the same with the shield as without it. This result is very important in the study of incidental shielding in the tunnels of a motor armature. It shows that while the force acting on the wire and shield is in no way diminished by the presence of the shield, the force which tends to move the wire relatively to the shield is very much diminished so that the insulation of the wire separating the wire from the shield does not have to bear any excessive mechanical stress. It is as if the small material insulation were considerably reinforced by the immaterial ether that fills the space between the wire and shield.

14. DIFFERENTIAL SHIELDING

The most important practical use of shielding is the protection of moving-magnet galvanometers against the steady terrestrial field in which they work. The galvanometers are generally of the astatic type. In practise it is nearly impossible to get the necessary exact balance between the two opposing magnets of the system. By using a cylindrical shield and adjusting it vertically so as to shield the magnets unequally, it has been found possible to compensate exactly for the inequality of the moving magnets by a corresponding inequality of the shielding and thus to increase the sensitivity of the galvanometer. This method of differential shielding is however not efficient against variable stray fields which often occur in practise.

Appendix

MATHEMATICAL THEORY OF ZONAL HARMONICS

15. ZONAL HARMONIC COEFFICIENTS

In Section 7, a simple spherical harmonic has been defined as the potential at any point A due to a harmonic magnet. A harmonic magnet of any order gives rise to a spherical harmonic of the same order.

(1) Let M_0 be a harmonic magnet of the zero order of strength M_0 , that is, a single magnetic pole of strength $+M_0$, located at the origin of the coordinate system (Fig. 4-0).

Let the coordinates of A be x, y , or r, θ . Then the potential at A due to the pole $+M_0$ at 0, is

$$V_0 = M_0/r \quad (19)$$

For unit magnet, ($M_0 = 1$) the potential

$$v_0 = 1/r \quad (20)$$

(2) Let M_1 be a harmonic magnet of the first order, that is, a single short magnet of magnetic moment M_1 . (Fig. 4-1).

Let $a b$ be the given harmonic magnet, that is, a single magnet with poles $+m$ and $-m$, located at points a and b on the prime vector, that is, on axis X at distances $+\delta x$ and $-\delta x$, so that $2m \cdot \delta x = M_1$.

We might assume both poles located at 0 to start with, and then each displaced over the distance δx , $+m$ to the positive side and $-m$ to the negative side. Potential at A due to $+m$ at 0 (before displacement)

$$V_0 = m v_0 = m/r$$

Potential at A after displacement of $+m$ is

$$V_0 + \delta V_0 = m (v_0 + \delta v_0) = m \left(v_0 + \frac{d v_0}{d x} \cdot \delta x \right)$$

Similarly for the negative pole $-m$, at $-\delta x$

$$V_0 - \delta V_0 = -m \left(v_0 - \frac{d v_0}{d x} \cdot \delta x \right)$$

resultant potential at A

$$\begin{aligned} V_1 &= m \left(v_0 + \frac{d v_0}{d x} \cdot \delta x \right) - m \left(v_0 - \frac{d v_0}{d x} \cdot \delta x \right) \\ &= 2m \cdot \frac{d v_0}{d x} \cdot \delta x = M_1 \cdot \frac{d v_0}{d x} \end{aligned} \quad (21)$$

For unit harmonic magnet ($M_1 = 1$)

$$v_1 = \frac{d v_0}{d x}$$

By evaluating the differential we get,

$$v_1 = \frac{d v_0}{d x} = \frac{d v_0}{d r} \cdot \frac{d r}{d x} = \frac{d}{d r} \left(\frac{1}{r} \right) \cdot \frac{d r}{d x}$$

But when $d x$ is positive $d r$ is negative, and $d r/d x = -\cos \theta$. See Fig. 4-1; therefore,

$$V_1 = -\frac{1}{r^2} \cdot (-\cos \theta) = \frac{1}{r^2} \cos \theta$$

$$\text{and } V_1 = \frac{M_1 \cdot \cos \theta}{r^2}$$

(3) By following the same reasoning, we obtain in general,

$$v_{(n+1)} = \frac{d}{d x} (v_n) \quad (23)$$

Therefore, by successive differentiation, we obtain the series of harmonics of successive orders.

$$V_0 = M_0 \cdot \frac{1}{r} \quad (24-0)$$

$$V_1 = M_1 \cdot \frac{1}{r^2} \cdot (\cos \theta) \quad (24-1)$$

$$V_2 = M_2 \cdot \frac{1}{r^3} \cdot (3 \cos^2 \theta - 1) \quad (24-2)$$

$$V_3 = M_3 \cdot \frac{1}{r^4} \cdot 3 (5 \cos^3 \theta - 3 \cos \theta) \quad (24-3)$$

$$V_4 = M_4 \cdot \frac{1}{r^5} \cdot 3 (35 \cos^4 \theta - 30 \cos^2 \theta + 3) \quad (24-3)$$

$$V_5 = M_5 \cdot \frac{1}{r^6} \cdot 15 (63 \cos^5 \theta - 70 \cos^3 \theta + 15 \cos \theta) \quad (24-5)$$

$$\begin{aligned} V_6 &= M_6 \cdot \frac{1}{r^7} \cdot 45 (231 \cos^6 \theta - 315 \cos^4 \theta \\ &\quad + 105 \cos^2 \theta - 5) \end{aligned} \quad (24-6)$$

$$\begin{aligned} V_7 &= M_7 \cdot \frac{1}{r^8} \cdot 315 (429 \cos^7 \theta - 693 \cos^5 \theta \\ &\quad + 315 \cos^3 \theta - 35 \cos \theta) \end{aligned} \quad (24-7)$$

The corresponding values of v_0, v_1, v_2 , etc., for unit magnets can be easily obtained by making M_0, M_1, M_2 , etc., equal to unity. The θ -function factor together with the numerical factor in each of the above equations is called a zonal harmonic coefficient; it is indicated by the symbol Z . It may be noted as an aid to memory that the numerical factor, together with the numerical coefficient of the highest power of $\cos \theta$ in the parenthetic term, make an odd-factorial of the corresponding order. For example in the value of V_7 we have, 315 . 429

$$\begin{aligned} &= (5 \cdot 7 \cdot 9) (3 \cdot 11 \cdot 13) \\ &= 1 \cdot 3 \cdot 5 \cdot 7 \cdot 9 \cdot 11 \cdot 13. \text{ (seven suc-} \\ &\quad \text{cessive odd factors beginning with 1.)} \end{aligned}$$

Using the symbol Z , the series of harmonics can be written in a very compact form.

$$V_0 = \frac{M_0}{r} \cdot Z_0$$

$$V_1 = \frac{M_1}{r^2} \cdot Z_1$$

$$V_2 = \frac{M_2}{r^3} \cdot Z_2$$

or generally

$$V_n = \frac{M_n}{r^{(n+1)}} \cdot Z_n \quad (25)$$

The power of r being always one degree higher (negative) than the order of the harmonic.

Then the potential at A due to the joint effect of all the harmonic magnets is,

$$\begin{aligned} V_A &= V_0 + V_1 + V_2 + V_3 + \text{etc.} \\ &= \frac{M_0 \cdot Z_0}{r} + \frac{M_1 \cdot Z_1}{r^2} + \frac{M_2 \cdot Z_2}{r^3} + \text{etc.} \end{aligned} \quad (26)$$

The potential V_A at any point A , may be thus regarded as made up of components V_0, V_1, V_2, V_3 , etc., each component being a simple spherical harmonic, and being the potential at that point due to corresponding harmonic magnets of strength M_0, M_1, M_2 , etc., respectively. It will be shown later that the potential at any point due to any kind of magnetic distribution subject to certain limitations can be analyzed into harmonics, appropriate strengths being assigned to the harmonic magnets necessary for the analysis; that is, the potential V_A at any point A in space, due to any kind of magnet distribution symmetrical with respect to an axis, can be analytically expressed by the series

$$V_A = \frac{M_0 Z_0}{r} + \frac{M_1 Z_1}{r^2} + \frac{M_2 Z_2}{r^3} + \text{etc.} \quad (27)$$

where M_0, M_1, M_2 , etc., are harmonic magnets of determinable strengths.

Equations (26) and (27) though identical in form are opposed in the mathematical sense. Equation (26) is synthetic: the value of V_A is computed from the values of M_0, M_1, M_2 , etc., which are supposed to be known. Equation (27) is analytic: in this case, V_A is supposed to be known and the values of M_0, M_1, M_2 , etc., are to be determined by analytical process; that *such an analysis is always possible*, is the basic idea underlying Equation (27), and therefore underlying the theorem formulated in Section 6. (For proof of this theorem see Section 17.)

16. GEOMETRIC AND HARMONIC IMAGES

(1) Geometric Image, (see Fig. 6).

Let $T A T'$ be the surface of sphere of radius r , and with center O .

Let Q be a single positive magnetic pole of strength q .

Let P be a point, inverse to Q , that is so related geometrically to Q , that,

$$OP = OA^2/OQ, \text{ or } a = r^2/d, \text{ or } \frac{a}{r} = \frac{r}{d}$$

Let p be the strength of an imaginary magnetic pole at P so related to q , that $p = q \cdot a/r = q \cdot r/d$.

Then p is called the geometric image of q in relation to the surface of the sphere, because the potential at any point on the sphere due to p at P , is the same as that due to q at Q . (See Eq. (28).)

$$V_q = Q/AQ = q/L$$

$$V_p = p/AP = p/R$$

By the well-known geometric properties of a sphere, we have in the triangles AOP , and AQO

$$\frac{OP}{OA} = \frac{OA}{OQ} = \frac{AP}{AQ}$$

$$\text{or} \quad \frac{a}{r} = \frac{r}{d} = \frac{R}{L}$$

therefore, $R = L \cdot a/r$

Substituting for p and R in the value of V_p ,

$$V_p = q \cdot \frac{a}{r} \cdot \frac{r}{L \cdot a} = \frac{q}{L} = V_q \quad (28)$$

This relation is true for all positions of A on the surface

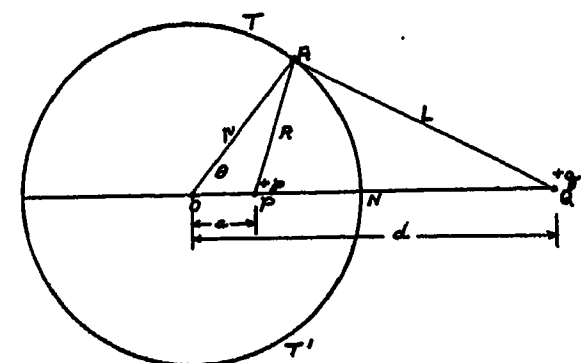


FIG. 6—GEOMETRIC AND HARMONIC IMAGES

of the sphere. Since p at P produces the same potential as q at Q , for all points on the sphere, p is called the image of q (geometric) in relation to the sphere.

(2) Harmonic images: Analysis of magnet pole into harmonic images.

The potential at A due to a pole p at P , is

$$\begin{aligned} V &= p/R \\ &= p \cdot (r^2 - 2ar \cos \theta + a^2)^{-1/2} \\ &= \frac{p}{r} \left[1 - \left(\frac{2a \cos \theta}{r} - \frac{a^2}{r^2} \right) \right]^{-1/2} \\ &= \frac{p}{r} \cdot \left[1 + \frac{1}{2} \left(\frac{2a}{r} \cos \theta - \frac{a^2}{r^2} \right) \right. \\ &\quad + \frac{1}{2} \cdot \frac{3}{4} \left(\frac{2a}{r} \cos \theta - \frac{a^2}{r^2} \right)^2 \\ &\quad \left. + \frac{1}{2} \cdot \frac{3}{4} \cdot \frac{5}{6} \left(\frac{2a}{r} \cos \theta - \frac{a^2}{r^2} \right)^3 + \text{etc.} \right] \end{aligned}$$

(See Pierce's Integrals, Table No. 750.)

Expanding the parenthetic terms and rearranging according to powers of $\frac{a}{r}$, we get

$$\begin{aligned}
 V = & \frac{p}{r} \left[1 + \frac{a}{r} (\cos \theta) \right. \\
 & + \frac{a^2}{r^2} \cdot \frac{1}{2} (3 \cos^2 \theta - 1) \\
 & + \frac{a^3}{r^3} \cdot \frac{1}{2} (5 \cos^3 \theta - 3 \cos \theta) \\
 & + \frac{a^4}{r^4} \cdot \frac{1}{8} (35 \cos^4 \theta - 30 \cos^2 \theta + 3) \\
 & + \frac{a^5}{r^5} \cdot \frac{1}{8} (63 \cos^5 \theta - 70 \cos^3 \theta + 15 \cos \theta) \\
 & + \frac{a^6}{r^6} \cdot \frac{1}{16} (231 \cos^6 \theta - 315 \cos^4 \theta + 105 \cos^2 \theta - 5) \\
 & + \frac{a^7}{r^7} \cdot \frac{1}{16} (429 \cos^7 \theta - 693 \cos^5 \theta + 315 \cos^3 \theta - 35 \cos \theta) \\
 & \left. + \text{etc.} \right] \quad (29)
 \end{aligned}$$

We find that the value of V is made up of a series of terms resembling the group of harmonics (Equation 24-0, -7) except that the numerical factor accompanying the θ -function factor is different. These two factors together constitute the zonal harmonic coefficient (practical), briefly called the "zonal harmonic" and denoted by the Symbol P . The published tables of harmonics give the values of P , not of Z . It may be noted at this point that the two forms of zonal coefficient are related by a very simple relationship, namely,

$$Z_n = n! \cdot P_n \quad (29-2)$$

for example, from Equations (24-7) and (29),

$$Z_7 = 315 (429 \cos^7 \theta - 693 \cos^5 \theta + \text{etc.}) \quad (24-7)$$

$$P_7 = \frac{1}{16} (429 \cos^7 \theta - 693 \cos^5 \theta + \text{etc.}) \quad (29)$$

therefore,

$$\begin{aligned}
 Z_7/P_7 &= 315 \cdot 16 = (5 \cdot 7 \cdot 9) \cdot (2 \cdot 4 \cdot 2) \\
 &= 5 \cdot 7 \cdot 3 \cdot 2 \cdot 4 \cdot 6 = 1 \cdot 2 \cdot 3 \cdot 4 \cdot 5 \cdot 6 \cdot 7 = 7!
 \end{aligned}$$

As an aid to memory it may be noted that the numerical factor in P is the reciprocal of the sum of the numerical coefficients in the bracketed part of P ; for example,

$$P_7 = \frac{1}{16} (429 \cos^7 \theta - 693 \cos^5 \theta + 315 \cos^3 \theta - 35 \cos \theta)$$

here, $429 - 693 + 315 - 35 = 744 - 728 = 16$.

In other words, the numerical factor is such as to make

$P = 1$ for all orders when $\theta = 0$, and $\cos \theta = 1$; this relation makes it very convenient both for the maker and for the user of the tables of harmonics, when expressed in terms of P instead of Z . For graphic

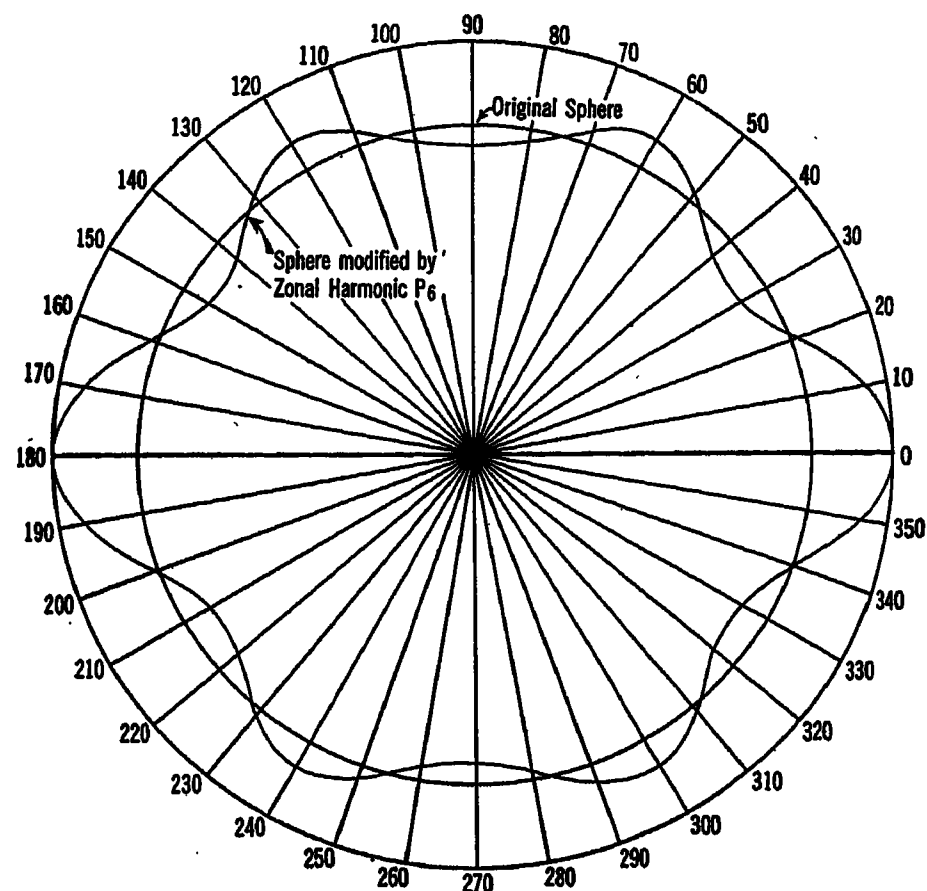


FIG. 7-6

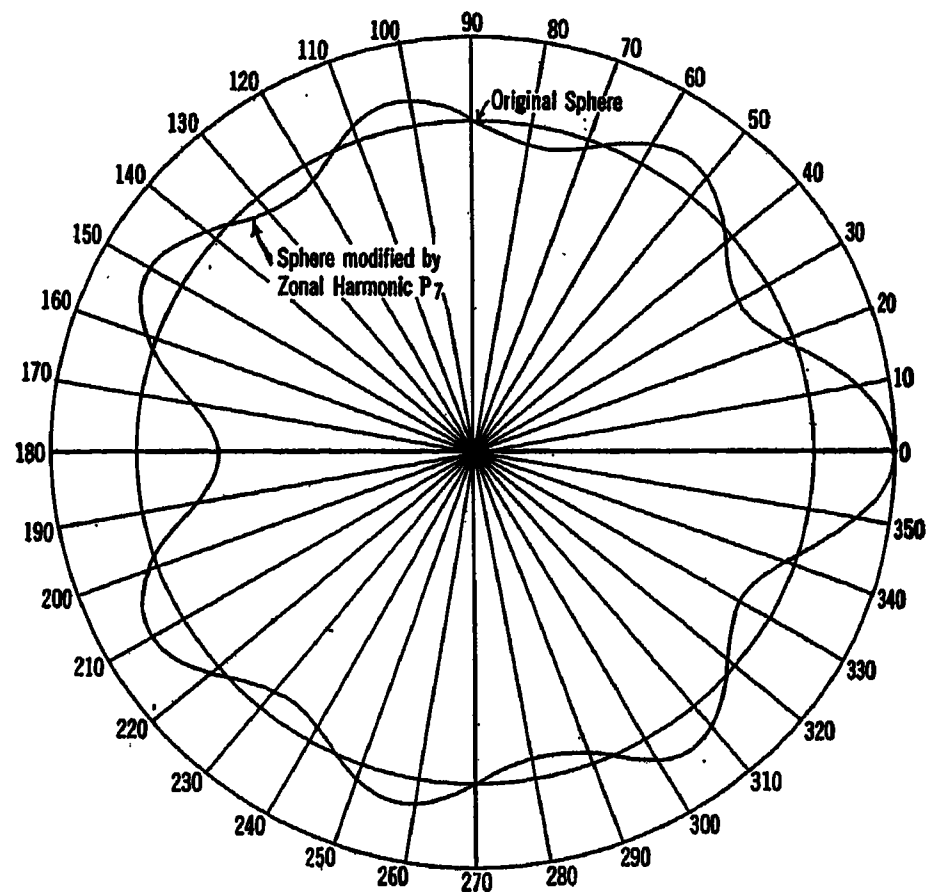


FIG. 7-7

FIG. 7—POLAR GRAPHS FOR ZONAL HARMONICS; SUBNUMBERS REFER TO ORDER OF HARMONIC

representation of zonal harmonics, see Figs. 7-6 and 7-7.

Using the symbol P , Equation (29) can be expressed in a compact form

$$V = V_0 + V_1 + V_2 + V_3 + \text{etc.} \quad (30)$$

$$= \frac{p}{r} \cdot P_0 + \frac{p a}{r^2} \cdot P_1 + \frac{p a^2}{r^3} P_2 + \frac{p a^3}{r^4} P_3 + \text{etc.}$$

(30-2)

$$\text{or } V = \sum \left\{ \frac{p a^n \cdot P_n}{r^{(n+1)}} \right\}$$

(31)

$$\text{or } V = \sum \left\{ \frac{B_n \cdot P_n}{r^{(n+1)}} \right\}$$

(31-2)

where B_n is an abbreviation for $p a^n$.

The general term of this series can be expressed as

$$V_n = \frac{p a^n \cdot P_n}{r^{(n+1)}} = \frac{B_n \cdot P_n}{r^{(n+1)}} \quad (31-3)$$

This equation resembles Equation (25), viz.

$$V_n = \frac{M_n \cdot Z_n}{r^{(n+1)}} = \frac{M_n \cdot P_n \cdot n!}{r^{(n+1)}}$$

They become identical if

$$B_n = M_n \cdot n!$$

or

$$M_n = \frac{B_n}{n!} = \frac{p \cdot a^n}{n!} \quad (32)$$

wherein, B_n and M_n are both independent of r .

This equation therefore gives the analysis of a pole p at the point P inside the sphere, into a series of harmonic magnets; the corresponding potential is analyzed at the same time into a series of spherical harmonics. Each of the harmonics is made up of three factors, one factor being a zonal harmonic P_n . Equation (32) shows that the several terms in the series in Equations (29) and (30-2) can be identified with the harmonics in the series of Equations (24-0) to (24-7) by giving appropriate values to M , that is by proper choice of the strength of the harmonic magnet required. Thus we have

$$M_0 = p = q \cdot \frac{r}{d} \quad (32-0)$$

$$M_1 = p \cdot a = q \cdot \frac{r}{d} \cdot \frac{r^2}{d} \quad (32-1)$$

$$M_2 = p \cdot a^2/2! = q \cdot \frac{r}{d} \cdot \left(\frac{r^2}{d} \right)^2 / 2! \quad (32-2)$$

$$M_3 = p \cdot a^3/3! = q \cdot \frac{r}{d} \cdot \left(\frac{r^2}{d} \right)^3 / 3! \quad (32-3)$$

$$M_4 = p \cdot a^4/4! = q \cdot \frac{r}{d} \cdot \left(\frac{r^2}{d} \right)^4 / 4! \quad (32-4)$$

etc.

etc.

The series for V may also be analyzed directly in terms

of q and d instead of in terms of p and a , as shown in the second form of each of the above equations.

Since $p/r = q/d$, and $a/r = r/d$, we have from Equations (30) and (30-2)

$$V = V_0 + V_1 + V_2 + V_3 + \text{etc.} = \frac{q}{d} \cdot P_0$$

$$+ \frac{q}{d} \cdot \frac{r}{d} \cdot P_1 + \frac{q}{d} \cdot \frac{r^2}{d^2} \cdot P_2 + \frac{q}{d} \cdot \frac{r^3}{d^3} \cdot P_3 + \text{etc.}$$

(33)

$$\text{or } V = \sum q d^{-(n+1)} r^n P_n = \sum (A_n r^n P_n) \quad (33-2)$$

Where A_n is like B_n , an abbreviation constant, and stands for $q/d^{(n+1)}$. A_n is independent of r , but the corresponding value of M_n is a function of r .

This equation gives the analysis of the pole q at the point Q outside of the sphere, into a series of harmonic magnets. The corresponding potential is expressed as a series of simple spherical harmonics, with the corresponding zonal harmonics as one of the factors in each term.

Note: The above method of analysis of potential at a point on the surface of a sphere, due to a pole located any where, in terms of Zonal Harmonics, was introduced by Legendre.

17. ANALYSIS OF ANY MAGNETIC FIELD IN GENERAL INTO COMPONENT SPHERICAL OR ZONAL HARMONICS

In the case of two magnetic poles, one inside the sphere and the other outside, the potential due to both the poles jointly is,

$$V = \sum A_n r^n P_n + \sum B_n r^{-(n+1)} P_n \quad (34)$$

The case of general magnetic distribution does not need elaborate analysis. Equation (34) leads to the conclusion, that since each point of the distribution has its corresponding harmonic magnets, it produces its share of potential which on analysis resolves into a series of harmonics. The aggregate effect is therefore also a sum total of harmonics which resolves itself into two groups, one of the type $A_n r^n P_n$, for all the poles outside of the sphere, and the other of the type $B_n r^{-(n+1)} P_n$ for all the poles inside of the sphere, the harmonic magnets corresponding to each point, being oriented along the radius vector for that point. If the distribution be symmetrical all the harmonic magnets lie on the axis of symmetry. Therefore,

Every symmetrical magnetic distribution can be represented analytically by a system of harmonic magnets, lying on the axis of symmetry which may be the prime vector; the potential at any point on the surface of an arbitrarily selected sphere can then be expressed analytically by two series of spherical harmonics, one series representing the effect of the external distribution and expressed by the typical form

$$V_e = A_n r^n P_n \quad (35)$$

and the other representing the effect of the internal distribution and expressed by the form

$$V_i = B_n r^{-(n+1)} P_n \quad (35-2)$$

Therefore for the two distributions together we have the analytical expression

$$V = \sum A_n r^n P_n + \sum B_n r^{-(n+1)} P_n \quad (36)$$

$$= \sum A_n r^n + \sum \frac{B_n}{r^{(n+1)}} P_n \quad (36-2)$$

This is the basic equation underlying the method of spherical harmonic analysis. (See Rucker's "Shielding of Concentric Spherical Shells," *Philosophical Mag.*, 1894, Vol. 37, p. 97.) In the case of a simple magnetic field, the analysis of the distribution which produces that field can be reduced to two simple terms each of the first order, that is,

$$V = (A_r + B/r^2) \cos \theta \quad (37)$$

This potential being produced by two harmonic magnets of the first order, that is by two simple magnets, both located at the center of this sphere and oriented in the direction of the field under analysis, one magnet representing the distribution inside the sphere, if any, and the other term representing the external. The problem of shielding a galvanometer placed in a uniform field belongs to the second class; in this case the expression for potential on the surface of a sphere reduces itself to the single term

$$V = A_r \cos \theta \quad (37-2)$$

which leads to considerable simplification of the shield problem.

Discussion

Hans Lippelt: The brightest spots in Mr. Gokhale's paper are certainly the results, which he presents in his own clear fashion and to which he attaches valuable ready-to-use utility.

The reader will not only absorb with interest the revelations of Equations 9 to 17 and their subsidiaries, but will surely enjoy the neatness by which these formulas take care of the geometrical form of and difference between individual shells.

The revelation of those formulas that two concentric shells of iron, separated by a concentric air space, give a greater shielding effect than one solid shell filling all the space with iron, may now be explained by the statement, that the magnetic reluctance of the outer shell (although higher than that of the solid shell) is sufficiently low to take care of the flux. At the same time the outer shell carries the flux past the shielded central area at a greater mean distance than the solid shell would do.

The high magnetic reluctance of the air space occurring between the shells of a two- (or multi-) shelled shield certainly comes very much into evidence as the real shielding power, inasmuch as the flux encounters a low reluctance (low magnetic potential gradient) in the outer shell.

Therefore, is it not the air space between the shells that does the shielding, while the outer shell does the carrying?

The inner shell, of course, carries only whatever little flux may have been crowded inward from the outer shell.

The air space within the inner shell appears then to be its own shield against the remainder of flux, carried by the inner shell. We will call this type of shield, which functions upon the low gradient of magnetic potential in the adjacent medium in conjunction with its own high magnetic reluctance, a Magnetostatic Shield.

It is known that for small magnetomotive force (H) the permeability for magnetizable metals is small. With increasing

magnetomotive force the permeability rises to a maximum, after which it falls off again. Since stray fields against which galvanometers and similar apparatus are to be protected, are mostly weak fields (H), the question arises as to whether Equation 9 covers only such weak fields, or whether it holds true when strong magnetic fields are to be shielded off. Should the gradient $d\mu/dH$, which may be positive or negative,¹ be considered in applying the formula?

Since a galvanometer may be moved from one room into another location, it may become necessary to check Equation 9 for reversal of stray field. Traces of hysteresis, which occur even in the best iron, may react upon the shield factor and impair the accuracy of measurements.

Hysteresis will entail a reversal of sign of μ when H and B respectively change sign. Such change in the sign of μ would greatly affect the answer which Equation 9 gives about the shield factor.

All these conditions are better overseen and understood when magnetic tension and magnetic friction are taken into account. (See A. I. E. E. TRANS., 1926, p. 406, under VII.) κ instead of μ becomes the important factor and there is no reversal of sign of κ .

Be it noted that the appearance of μ in formula (9) indicates that not only the original field H has been taken care of, but also the increase in flux, occasioned through the introduction of iron (shell) into that field.

In Section 9, "Material for Shells," Mr. Gokhale says:

"The impulsive nature of the disturbance generates an eddy current, which chokes back a part of the flux and prevents it from going through the walls of the shell, thereby reducing the efficiency of the shell as is indicated by an impulsive kick of the protected galvanometer."

That does not seem quite clear. If the eddy current "chokes back" and "prevents the magnetic impulse from going through the shell," that would mean demonstrating the efficiency of the shell, not reducing it. If the galvanometer gets only a kick out of a heavy transient, the shield must have done good work.

Besides in this case of a transient magnetic disturbance the massive shell itself has acted as a shield through the medium of the eddy current, which chokes back part of the flux and prevents it from entering the central area.

Here the shell acts as a magnetodynamic shield and in addition also carries the flux.

That laminated shields, rolled with copper spacer, are more efficient than the shell made of iron only, needs hardly any further explanation, when seen in the light of magnetodynamic shielding; I believe that a copper shell placed outside of a massive iron shell will render the outfit strongly efficient against magnetic transients.

A better explanation of the subject treated on page 1310, fifth paragraph, may be in order. Does pole $+m$ move over distance dx in direction of $+X$, with $-m$ remaining in the origin of the system? Or does $+m$ move $+\frac{1}{2}dx$ and $-m$ move $-\frac{1}{2}dx$? This should be cleared up to make the next paragraph readily understandable.

Similarly the reader should observe that the term "strength of the magnet" is used in two different ways, see page 1309, col. 2.

The "polar strength m " fits in well with the moment $M = m \cdot 2a_1$. Five lines further down one reads of harmonic magnet of strength M_1 (which is $m \cdot 2a_1$) and further down . . . strength of the magnet of n th order $M_n = m \cdot 2a_n - 1 \dots 2a_2 \cdot 2a_1$. The unit by which to measure such harmonic magnets changes by a linear dimension, geometrically, at each step. This is not conducive to forming a concrete concept of those magnets.

In consideration of such conditions it may be said of this paper, that the results are admirable. The method, however, consists in pressing a very pliable mathematical material into the very

1. See J. A. Ewing, "Magnetic Induction in Iron & Other Metals," Van Nostrand, 1900, 3rd ed., pp. 126 and 143.

rigid mold of an intricate problem, and thus is a great accomplishment of its own kind.

S. L. Gokhale: Mr. Lippelt's first contribution is an effort to explain the phenomenon of shielding, once more in terms of reluctance. I do not say that it cannot be done, but for reasons already explained in Section 4 of the paper, I doubt whether any such explanation is worth the effort. The chief merit of the reluctance conception is simplicity; its chief demerit is the failure to explain the phenomenon in all its phases except at the cost of simplicity which is its only merit. Even after a careful study of Mr. Lippelt's comments on this point, I do not feel that he has succeeded in combining simplicity with accuracy.

For example, let us concede for sake of argument that Mr. Lippelt's explanation is correct, and that the most important part of the work in the process of shielding is done by the intermediate shell of air space, and that the outer shell merely helps the process by providing a by-pass to the flux, and that it should therefore be so designed as to be able merely to carry this flux, any excess material being merely a waste. It would follow that for the most efficient shield the relative thickness of the magnetic shells in comparison with the air shells, should be determined by the permeability of the material. This is contrary to the corollary from Rucker's formula which requires the shells to have the same ratio p (see Equation 9) for all shells, magnetic and non-magnetic, irrespective of permeability of the magnetic material;

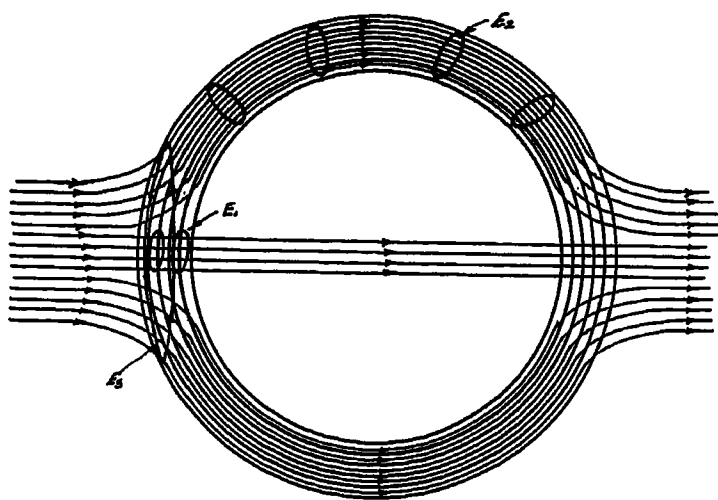


FIG. 1

(see statement following Equation 17). Again I do not suggest that it is impossible to account for all these facts by an explanation based on reluctivity; my contention is merely that it cannot be done without sacrificing simplicity, and is therefore not worth trying. I only mean that it is not worth trying to explain the phenomenon directly in terms of reluctivity, but the best interpretation can be made indirectly in terms of some intermediate conception, with the conception of reluctivity in the background. This is exactly what Rucker has done in his analysis. After writing down the potential equation for a spherical surface in general, he selects a boundary surface separating two shells, and writes for this surface, the two equations of magnetic refraction; the value of H in these two equations is derived from the basic harmonic equation (Equation 6) by differentiation. These two equations involve the conception of reluctivity, so that we have in this method of harmonic analysis not a method opposed to, or even independent of the reluctivity conception, but a method in which reluctivity is kept out of view to prevent its complicating the explanation while pretending to simplify it.

With reference to hysteresis, it is frankly admitted that Rucker's and DuBois' formula for shield factor as a function of permeability, (B/H) , based on the assumption that this ratio is constant, is only a first approximation, (see Section 10). A closer approximation requires us to take into account not only the variation in the value of permeability according to flux density at every point

of the shield material, but also the effect of hysteresis, which includes differential permeability. Mr. Lippelt says that this ought to be done, and I certainly agree with him. But my next question is, "Who will bell the cat?" Rucker could not do it; Du Bois could not do it; I do not expect to be able to make even a beginning in that direction. If Mr. Lippelt feels like tackling the problem, he is welcome to it. About thirty-five years ago Dr. Steinmetz had criticized adversely a scientific paper on the ground that it was imperfect inasmuch as it had ignored the third harmonic. The original author in his reply acknowledged the imperfections and offered the apology that the proper treatment of the problem with computation for the third harmonic was beyond the reach of the engineering science of the day. Dr. Steinmetz accepted the implied challenge, made the necessary correction, and as a consequence the engineering science was enriched by that contribution. If as a result of my apparent challenge the scientific world is made richer through Mr. Lippelt's formula for shield factor I shall certainly feel proud of my indirect share in the work.

With reference to the eddy currents and their effects on shield factor Mr. Lippelt's point seems to be well taken. As I see it now, the statement has certainly suffered in point of clearness by attempting too much abbreviation. I hope the following explanation will make clear the nature of the phenomenon:

Imagine a tube of flux lines going through a spherical shell: Some of the lines cross the walls of the shell and penetrate the shielded space; but a greater number of lines bend round and follow the shell walls, their number depending on the design of the shell and on the permeability of the material. The first group of lines tends to produce the eddy system e_1 , which in turn chokes back a part of this group and diverts the lines along the path of the second group, thereby improving the efficiency of the shield. The second group produces the eddy system e_2 which in turn chokes back a part of this group and sends it along the path of the first group, thereby impairing the efficiency of the shield. A third eddy system e_3 , produced jointly by both groups, is unimportant and needs no consideration. The systems e_1 and e_2 have opposing tendencies, and the final result depends on the relative strengths of the two systems. If the shell be made of massive material, the system e_2 is very much stronger than e_1 , which greatly impairs the efficiency. If the shell is laminated the system e_2 is considerably weakened, but e_1 is practically unaffected, the aggregate result being that the efficiency of such a shield is nearly as good for impulsive stray fields, as for steady fields. For the same reason alternate sheets of copper lead to further improvement of the shields as they further strengthen the system e_1 without strengthening e_2 .

With reference to the displacement conception of the harmonic magnets, Maxwell prefers the displacement of one pole along the axis, the other pole being left undisturbed at the center. I have preferred in my computation, equal and opposite displacements of both poles (see Section 15, derivation of Equation 21). Mathematically, it makes no difference in the final results, and for this reason I have left the point unspecified in the definition using a more flexible phrase "stretched apart" without specifying whether both or only one was displaced.

With reference to the "strength" of a harmonic magnet, the theoretical definition is implied rather than expressed mainly for the sake of brevity. The strength of anything is measured by what it can do. The function of a magnet is to produce a magnetic field and this function is mathematically best expressed in terms of potential. The strength of a harmonic magnet may therefore be defined as the potential at some specified point, due to that magnet; for practical use, the strength of a harmonic magnet is defined as the potential of that point at unit distance from the center of the harmonic magnet, and located in the direction of its orientation; a unit harmonic magnet is one which produces unit potential at that point. This definition is implied, but not explicitly stated by Maxwell. It can be shown that the

value of the potential can be expressed in terms of the strength of the poles and the interpolar distances of the harmonic magnet. The strength of the magnet therefore may also be defined analytically in terms of poles and interpolar distances; this is what I have done. This mode of defining has the merit of avoiding any appearance of argument in a circle, involved by first defining

strength in terms of potential and then expressing potential in terms of strength.

The fact that the linear dimensions of strength vary with the order of the harmonic magnet constitutes no valid objection to this mode of definition. This peculiarity is inherent in the nature of the concept defined.

Automatic Stations

ANNUAL REPORT OF COMMITTEE ON AUTOMATIC STATIONS*

To the Board of Directors:

INTRODUCTION

This terminates the second year of the existence of this committee. The field of action in which this relatively new committee finds itself is so broad and has so many inviting by-ways that it has been difficult to outline the work. The engineering in connection with the application of automatic control is so fascinating as to result in so many new ideas being steadily developed that the fundamentals are sometimes almost overlooked. It is indeed amazing to realize the changes in ideas which occur in this branch of the industry in a single year. This committee attempts in the following report to outline some of the development and offer suggestions which are intended to benefit this branch of the industry.

SCOPE

The scope of work of this committee covers automatic and partially automatic generating stations and substations, the committee having complete jurisdiction over all apparatus associated with such stations. In addition the committee has jurisdiction over systems of remote dispatching, control, indications, etc., associated with the industry. The committee is interested in the dissemination of the knowledge and experience already gained in the design and operation of such equipment and combinations thereof, in order that this branch of the industry may be more fully developed.

ECONOMICAL CONSTRUCTION

The developments of the year indicate a general tendency to take advantage of the economical construction possible with the use of automatic stations. It is still hard to realize the radical difference in station arrangement and set-up between the old firmly rooted manual system of operation and modern automatic operation. We are beginning to see, however, that the presence of a human mind and body in the manual station had a marked effect on station arrangement and that mechanical and electrical things were done solely because of the safety, comfort, and convenience of this human presence. Automatic control has all but eliminated this human body and has moved the mind from the station to the office of the engineer.

It is believed that one of the most radical and eco-

nomical changes in station arrangement has been the elimination of the continuous switchboard. When this is studied it is found that there is no longer a necessity for assembling all of the control wiring from remote parts of a station at one point at the expense of thousands of feet of wire and conduit just to produce a switchboard assembly that makes a nice appearance.

The above is particularly true in a-c. substations and hydro-station applications where the details of control can and properly should be located as near the equipment controlled as is consistent with good fire protection and safety. It is now becoming common to see control panels located in various places throughout a station close to the equipment controlled, thus saving considerable in wire, conduit, and hazard.

Another saving has been realized from the reduction in size and in some cases the complete elimination of heating plants.

Ventilation has also been reduced, as in many cases a considerable amount of air was required over and above that actually required by the station apparatus for the comfort of the operating employees.

The problem of station location has been eased somewhat by the advent of automatic control as stations can now be located in places where it would be almost impossible to keep operating men on the job on account of the absence of what might be considered the proper amount of daylight, pure air, water, etc., necessary for the continuous maintenance of human beings.

RESEARCH AND DEVELOPMENT

Research during the past year has brought forward many improvements in detail apparatus which are contributing much to simplify the problems of application. Careful analysis of operating records disclosed the need of more simple means for the adjustment of equipment to meet a wide range of applications, particularly for the calibration of relays. Much has been done in this connection with the result that not only have improvements in relays simplified matters of calibration but by extending the range of application, the number of types of relays required has been reduced, thus greatly simplifying routine inspection and maintenance.

Simplified and improved supervisory control and remote metering systems have been produced as a result of experience with several very successful schemes in numerous applications.

Some work has been done in the development of devices for recording operations, quantities, etc., on charts, but this appears to be one of the weakest points in automatic development. There are devices available for recording almost anything desired but either they

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Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

are insufficiently reliable or their cost is prohibitive for extensive applications.

Simplified schemes of control for the automatic switching of rotating apparatus looking toward reduction in the number of moving parts are being tried out. The economics of application are being given a great deal of study. On a number of metropolitan street railway properties, the items of power consumption from the generating stations to the car wheels are being carefully analyzed. Operating voltages best suited to given operating areas will be selected and means for automatically or remotely controlling the substation apparatus for proper adjustment of the voltage to operating conditions will be provided.

Operators and careful analysis of operating results are the sources of information which will enable the manufacturers to develop new and improved equipment and to this end, it is urged that systematic and well-kept records be made available on operation, inspection, and maintenance. Well operated stations are the proving grounds and as essential to progress as the laboratory.

OPERATING REPORTS AND INSPECTION

The predecessors of this committee have stated that the art would advance much more rapidly if more operating engineers would avail themselves of the opportunity at Institute meetings to tell of their individual experiences, through papers and taking part freely in discussion. Your present committee wishes to emphasize this and add an invitation to correspond freely with the members of this committee on subjects of interest to the followers of the automatic art. It is felt that in this way the annual reports of this committee will be made more representative. With this idea in mind your committee has this year sent out questionnaires attempting to gather operating, maintenance, and inspection data from a wide field of experience, covering a variety of applications. While these questionnaires may be considered a burden by some, this committee feels that a great many engineers are vitally interested in the subject and are willing to furnish the data requested to the end that the art may be more universally applied and incidentally improved. Some answers to the questionnaire have been received but not sufficient to present a recapitulation in the pages of this report. This committee intends to turn this partly finished work over to its successors with the earnest recommendation that they carry it forward.

Inspection and maintenance of automatic plants may be catalogued into two general classifications, equality and quantity, depending entirely upon the continuity of service expected and demanded of the automatic plants, and by the individual managements.

The word "maintenance" is used advisedly in view of the fact that inspection and maintenance are so closely allied at times as to be almost inseparable.

The old phrase, "getting out of a thing what you put

into it" is exemplified in automatic station operation. However, the curve of failures of equipment to function plotted against dollars spent on inspection and maintenance, is not at all uniform, cost ratio increasing much more rapidly as the number of failures declines to the zero point. This point is clearly illustrated by a member of the subcommittee, and a pioneer in the automatic operation of a large metropolitan system, who states that two extremes are possible in automatic substation operation, under inspection and maintenance, and over inspection and maintenance.

A plant may be used for such a test, little or no inspection and maintenance being given during a predetermined period of time, observing the number of failures occurring, with their causes. By taking this number of failures as the unit, one hundred for example, and increasing inspection and maintenance, the failures will diminish rapidly to a point whereby 90 per cent of the one hundred will have been eliminated during an equal time period. At this point, inspection and maintenance can be doubled with the resulting effect of the elimination of only a few of the remaining ten failures. A happy medium between the two extremes is therefore logically assumed the most economical method of operation.

Past and present experience as reported by the various operating engineers, seems to disclose the fact that to function properly, automatic equipment should be given casual and periodical inspections. These inspections vary according to the needs and conditions of the individual installation, and the severity of service. The casual inspections on metropolitan systems as reported, are made as often as two hours apart during the heavy hours of the day, and two or three days apart on other systems and conditions.

These inspections usually consist in observing the functioning of equipment in service, overheated contacts, graphic chart clocks for time, inking, bearings, overheating, ventilation, etc. For stations outside of metropolitan districts, the casual inspections are likewise reported as being made daily on some systems, and weekly on others, ranging in the average of two or three times a week, with a tendency to make fewer inspections when the stations are equipped with supervisory control. The actual time required to make a casual inspection is much less than the traveling time.

A startling fact was disclosed when only about half of the 23 engineers replying to the questionnaire indicated that they followed any prepared method in inspection and testing but relied upon the field man entirely. It followed that in these cases no form was provided on which the field man could accurately report. Results from such a method must surely vary with the character and temperament of the inspector and cannot possibly be conducive to good operating and service results. Many of the replies, however, indicated the existence of very closely prescribed test and inspection methods along with very complete

records including very comprehensive classifications of device failures. That sort of practise, if universal, would most certainly pay dividends to the industry. This year's committee has become so intensely interested in this subject that the thought has occurred to attempt the standardization of test and inspection methods, forms, and failure classifications. It is felt that with standard forms in use this committee could be made a clearing house for much valuable information, thus permitting the designing engineers to profit by the mistakes of others as well as by their own.

In order to implant the thought we are herewith submitting a suggested form.

STANDARD AUTOMATIC SUBSTATION TROUBLE FORM

Date.....19.....	Station No.....
Device Which Failed.....	
Machine, Transformer or Circuit Number.....	
Nature of Failure.....	
Cause of Failure.....	
Consequences.....	
How Remedied.....	
Located By:.....	Repaired By:.....
Unit Out of Service from.....M.....	To.....M.....
What Load Actually Interrupted and for How Long.....	
What Load Otherwise Affected and for How Long.....	
Copies to:.....	
☒ CLASSIFICATION ☐ Improper Adjustment by Mfg. ☐ Improper Adjustment by Owner. ☐ Improper Application. ☐ Improper Assembly ☐ Improper Design. ☐ Lack of Proper Inspection by Owner. ☐ Defective Workmanship by Owner. ☐ Defective Workmanship by Mfg. ☐ Unforeseen Operating Conditions. ☐ Undetermined.	
Approvals:.....	

By the use of forms similar to the one herewith submitted, several operating companies have been able to detect particular devices, schemes of connection, etc., which persistently give trouble, and as a result have increased the reliability of their equipment to a considerable degree by correcting the troublesome elements. One company in addition to the classification of the failures shown on the form, classifies and records the failures under device numbers and types.

One of the companies sends copies of all trouble forms to the manufacturer of the equipment involved, thereby giving the manufacturer the opportunity to turn the experience into something profitable to both themselves and the user.

PAPERS

Six papers were presented to the Institute during the year on the general subject of automatic stations and were sponsored by this committee:

Automatic Mercury Arc Power Rectifier Substation on the Los Angeles Railway, by L. J. Turley, Spokane, Aug. 1928.

The Automatic Substation—Its Relation to Electric Distribution Systems, by S. J. Lisberger, Spokane, Aug. 1928.

Telemetering, by Linder, Stewart, Rex, and Fitzgerald, New York, Jan. 1928.

Automatic Mercury Rectifier Substations in Chicago, by A. M. Garrett, Cincinnati, Mar. 1929.

Automatic Reclosing of High-Voltage Circuits, by Robertson and Spurgeon, Dallas, May 1929.

Automatic Transformer Stations of Edison Electric Illuminating Co. of Boston, by W. W. Edson, Swampscott, June 1929.

STANDARDS

Standards for automatic stations (No. 26) were adopted and issued in 1928. It was realized that in view of the rapid progress of this branch of the industry it would be necessary to revise these standards from time to time. A subcommittee has worked out some desirable changes which are not voluminous enough to warrant a revision of the Standards as published. However, this committee will add to this group of changes from time to time, until it is felt that it is worth while to present them to the Standards Committee with recommendations.

BIBLIOGRAPHY

With the idea that a complete bibliography of automatic station literature would be of inestimable value to the electrical engineer, this committee published as an appendix to its report last year a complete bibliography up to the date of the report. A supplement covering literature published from the last report to March 1, 1929, is included as an appendix to this report. Acknowledgment with thanks is hereby given to the Main Library, General Electric Company, for this service.

SUPPLEMENTAL BIBLIOGRAPHY FOR 1929

(SUPPLEMENTING THE "BIBLIOGRAPHY OF AUTOMATIC STATION LITERATURE" IN A. I. E. E. TRANS., VOL. 47, OCT. 1928, PP. 1241-52)

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Discussion

Chester Lichtenberg: The "Economic Construction" portion of the committee's report calls attention to a new scheme, that of taking the switching units and putting them around the substations and generating stations. It might be interesting to call attention to the fact that this is a very distinct advance in design, whether for substations or generating stations, because it almost eliminates the control wiring and conduit. This reduces the cost of the station and eliminates the necessity for a separate switchboard room or switchboard gallery.

Under "Development," I had hoped that the Committee would list something about wiring symbols, because operators and manufacturers are having a great deal of trouble now getting the same wiring symbols for the same devices and for the same applications.

Telemetering is mentioned. The statement is made that it is relatively new, the devices are insufficiently reliable, and the costs are prohibitive for extensive applications. It is true the telemetering is relatively new, but the costs are being rapidly reduced. It is also true that the reliability of the equipment is improving. Some of the newer designs are just as reliable as the present-day voltmeters, ammeters, and watt-hourmeters. The

accuracy of telemetering is very nearly of the same order as that of conventional recording and indicating instruments. It is not quite equal to their accuracy, however. This is because, first, an indicating or recording instrument or its equivalent is used for originating the telemetering impulse, and second, the equivalent of an indicating or recording instrument is used for receiving the impulse. Consequently there are at least two instruments, sometimes three in series and, therefore, the errors are cumulative.

One of the difficulties about telemetering is misapplication. The manufacturer is not always given an opportunity to suggest the best design for a particular application, and sometimes is forced to go too far in advance of the art.

Another interesting item is in connection with supervisory equipment. Telephone relays or telephone-type relays are becoming more generally used. One thing about supervisory systems that is causing trouble is lack of standardization of voltage. One manufacturer supplies 24-volt lamps and another 48-volt; one uses 60 volts and 24 volts and another 48 volts. Probably the Committee on Automatic Stations ought to take this matter under advisement during the coming year.

It is interesting to note under "Development" that practically all of the mercury arc rectifiers which have been placed in service since 1927 have been made automatic. Only a few are manual.

It is also interesting to note that there are automatic stations in practically every country in the world. In this connection the British Electrical and Allied Manufacturers Association has asked our cooperation in making American standards uniform for Great Britain.

Nothing has been said this year about the minimum protection of apparatus. It is believed that the Committee on Automatic Stations for 1929-30 ought to give this subject some consideration, because it may be that the minimum protection to be required of apparatus may be reduced over present recommendations.

H. P. Sleeper: In this report reference is made to the matter of the importance of keeping accurate reports of operating results, particularly troubles which are experienced. I should like to add a plea to the reference and cite our own experience in connection with the keeping of operating records.

Approximately two years ago a system of reporting apparatus troubles on special forms provided for the purpose was instituted in our company. This form is filled out in the field and summarized in the general office. It contains all data pertinent to the identification of the apparatus involved such as serial, style, voltage, etc., together with a brief explanation of the trouble and its cause. These reports from all over the system are summarized by types and classes of apparatus and a summarized report is made annually.

This system of reporting apparatus troubles has been found to be invaluable. It is particularly useful to determine where the maintenance forces should concentrate their work in order to secure proper operation. It furthermore quickly picks out defective points in equipment by noting similar cases of trouble on equivalent types of equipment and enables the manufacturers to detect weaknesses that show up only under operating conditions. It further serves the purpose of enabling a very fair comparison to be made between similar equipments on the basis of operating results. By noting faults on a given type of equipment against inventory records on all equipment in use of that type, it is possible to reduce such records to a percentage basis and hence a very fair analysis is obtained on similar types of equipment made by different manufacturers.

I believe that a procedure similar to this should be carefully kept by all operating men as the results to be obtained are not only of local benefit but are of mutual benefit among operating companies because of the improved product which may be obtained from the manufacturers as a result of the operating records which are thus obtained.

Electrical Communication

ANNUAL REPORT OF COMMITTEE ON COMMUNICATION*

To the Board of Directors:

During the past year considerable progress has been made in the various branches of electrical communication engineering. The Committee on Communication submits the following report as a summary of the principal developments.

TELEPHONE TRANSMISSION

Work on improved telephone transmitting and receiving apparatus and amplifiers by the Bell System has made possible the completion of a new telephone transmission reference system, two copies of which have been built. One has been installed in New York in the Bell Telephone Laboratories, and the other in Paris under the auspices of the International Advisory Committee on Long Distance Telephony. The manufacture of these two reference systems forms a basis for world-wide agreement on the fundamental standards to be used in judging telephone transmission. A description of this equipment is given in a paper entitled *Master Reference System for Telephone Transmission*, by Messrs. Martin and Gray, scheduled for presentation at the 1929 Summer Convention.

Agreement has also been reached on the use of the fundamental unit of transmission, named the "bel." The transmission unit which has hitherto been used in this country is one-tenth the size of the bel and will therefore be known as the "decibel;" it will be continued in use in this country.

At the Winter Convention of the Institute, a paper on the subject of *Vector Presentation of Wave Filters* was presented by Messrs. Mallina and Knackmuss.¹

TELEPHONE SERVICE IMPROVEMENTS

With the increase of approximately \$275,000,000 in telephone plant investment for the country for the year 1928, toll telephone conversations increased 7½ per cent over 1927. The handling of these toll calls has been improved, both as regards speed and clearness of voice transmission. Toll calls are now handled on the average in 1.2 minutes and in over 95 per cent of the cases the subscriber remains at the telephone. Over 97 per cent of the long toll messages

are carried out without evidence of transmission difficulty or interruption.

Important developments in long distance telephone communication in Canada included the completion during 1928 of direct circuits between Montreal and the maritime provinces, between Toronto and Winnipeg, and between Calgary and Vancouver.

In several of the larger cities of the United States, the practise of telling the time of day to subscribers who call the number designated for this service has been initiated.

DIAL TELEPHONY

The dial service was rapidly extended, the number of dial telephones in the United States increasing approximately 600,000 during the year, with about 18 per cent of the total stations now on this basis.

This expansion in the service requires continued development work and in the dial system areas, general use of mechanical tandem equipment is rapidly extending. This applies not only to the largest areas, but to others as well; and to step-by-step areas as well as to panel.

For areas in which step-by-step equipment is used, the dial system "B" boards have been initiated. These boards make dials unnecessary on manual "A" positions which are required to operate into dial offices. Such equipment has been found satisfactory in operation, and its use is spreading.

CARRIER SYSTEMS

The most important advance in the art of carrier current telephony over telephone lines during the last year was the extensive application of short-haul single-channel carrier systems. About 200 of these were manufactured and installed, providing approximately 20,000 mi. of carrier circuit in place of wire stringing. This system was described in detail by Messrs. Black, Almquist, and Ilgenfritz at the Pacific Coast Convention in Seattle in a paper entitled *Carrier Current Systems for Short Toll Circuits*.²

The important advances which have been mentioned for the past few years in the annual reports along carrier current lines were described in detail in a paper entitled *Carrier Systems on Long Distance Telephone Lines*, presented at the Summer Convention in Denver by Messrs. Affel, Demarest, and Green.³ This paper also gave data showing the steady increase in commercial applications of these carrier systems.

In the field of carrier current communication over power lines there has been continued progress in im-

*COMMITTEE ON COMMUNICATION:

H. W. Drake, Chairman,		
G. R. Benjamin,	E. H. Everitt,	R. D. Parker,
H. P. Charlesworth,	D. H. Gage,	S. R. Parker,
F. J. Chesterman,	S. P. Grace,	F. A. Raymond,
L. W. Chubb,	E. Hausmann,	C. A. Robinson,
J. L. Clarke,	P. J. Howe,	J. K. Roosevelt,
R. N. Conwell,	H. L. Huber,	H. A. Shepard,
B. R. Cummings,	B. D. Hull,	J. F. Skirrow,
O. E. Davies,	G. A. Kositzky,	H. M. Turner,
R. D. Evans,	F. H. Kroger,	F. A. Wolff,
	R. H. Manson,	

1. A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 582.
Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

2. A. I. E. E. Quarterly TRANS., Vol. 48, January 1929, p. 117.

3. A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1360.

proving designs and at the same time increasing the simplicity of operation. Additional installations of carrier telephone equipment are continuing at a normal rate, and this type of equipment has a well defined place as a reserve means of communication. In several cases, particularly on high-voltage superpower systems, power companies are making use of carrier communication for dispatching purposes. This is particularly true in isolated locations where the commercial telephone plant has not developed sufficiently to meet the requirements for continuous service.

Interesting data on power line carrier current working are contained in the following papers: *Power Line Carrier Telephony*, by Messrs. Fuller and Tolson, and *Problems in Power Line Carrier Telephony*, by Messrs. Wolfe and Sarros, presented at the Pacific Coast Convention; *Transmission of High-Frequency Currents for Communication over Existing Power Networks*, by Messrs. Boddie and Curtis, and *Carrier Current and Supervisory Control on Alabama Power Company's System*, by Messrs. Robinson and Woodcock, presented at the Atlanta Regional Meeting.⁴

TELEPHONE PLANT

An outstanding feature in the past year has been the rapid extension of toll cable, there having been placed during the year about 2500 mi. of toll cable including more than one and one-third million miles of conductor. The continuous toll cable network now extends along the Atlantic seaboard north to Brunswick, Maine and south to Greensboro, North Carolina. Westward extensions on several separate routes have been carried to St. Louis, Missouri, and Davenport, Iowa. In Canada, the Hamilton-Buffalo and Toronto-Oshawa links have been completed.

An electrical alarm system has been developed for indicating the presence of moisture in telephone cables, as shown by low insulation. This system consists of a vacuum-tube alarm device which is connected successively after a suitable charging interval for a period of approximately 60 sec. to various conductors in the cable. To avoid interference with working circuits the test is made from the midpoint of the repeating coil on phantom circuits.

For the local plant, a cable has been developed containing 1818 pairs of 26-B&S gage wires. This compares with a previous maximum capacity of 1212 pairs. The new fine gage cable will be particularly useful in conserving duct space in congested metropolitan areas.

With the increasing demand for poles used in the construction of power and communication lines, new sources of supply must be developed. Mr. Lindsay's paper *Utilization of Lodgepole Pine Timber for Poles*,⁵ presented at the Summer Convention in Denver,

describes the method of selecting and using lodgepole pine, which has not hitherto been used to any appreciable extent for this purpose

TELEPHONE EQUIPMENT

A new form of information desk designed for greater convenience of reference and improved speed of answer has been developed. Improvements, particularly in connection with telephone booths and telephone station units, have been made and will result not only in better and more convenient apparatus but also in providing greater usefulness.

Improved dial system equipment particularly adapted for small private branch exchanges was made available during the year. This equipment has associated with it a small cabinet for desk mounting, which takes the place of a section of switchboard and is arranged so that the attendant's services are not required for disconnection, thus improving the over-all service and operating economies.

Private branch exchange equipment adapted to the requirements of large residences has also been developed. This equipment is intended to provide various special features which are in demand and also to introduce some improvements and simplifications.

The Bell System is experimenting with company operation of private branch exchanges with a view to improving this branch of the service.

To facilitate improvements in toll service to small outlying offices, a series of small power units particularly adapted for use in such offices to supply a few telephone repeaters, carrier terminals or telegraph circuits was developed.

DEVELOPMENTS IN MATERIALS

The basic conception of the insulating properties of textile insulation has been investigated by the engineers of the Bell System and it has been found that by suitable purification processes, the insulating properties can be materially improved. The process and results are described in a paper entitled *Purified Textile Insulation for Telephone Central Office Wiring*⁶ by Messrs. Glenn and Wood. A companion paper by Messrs. Williams and Murphy on the subject *Influence of Moisture and Electrolytes upon Textiles as Insulators*⁷ was presented at the same meeting.

During the year, the use of cellulose acetate has been extended materially, both in solid form and for impregnating textiles used in telephone work. Cellulose acetate is the base of the best grades of artificial silk, is non-inflammable, and has other valuable mechanical and electrical properties.

An important development of the Bell Telephone Laboratories has been a series of alloys of iron, nickel, and cobalt, known as the "perminvars." This develop-

4. A. I. E. E. Quarterly TRANS., Vol. 48, January 1929, pp. 102, 107, 227, and 214 respectively.

5. A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1354.

6. A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 576.

7. *Ibid.* p. 568.

ment is an outgrowth of the earlier discovery of perm-alloy. The new alloy has not only high initial permeability, but its permeability is constant to a remarkable degree. Its properties indicate that it will be very serviceable in certain types of communication equipment and systems.

AIRWAYS COMMUNICATIONS

An experimental trial of rapid telephone methods for collecting the necessary weather data is now being conducted in California by the Weather Bureau with the cooperation of the Guggenheim Foundation and the Pacific Telephone and Telegraph Company.

Another adaptation of wire services to airways communication is the use of telephone typewriter service. A number of installations has been made both for local communication at the airport and for communication between airports.

A description of a successful system of guiding airplanes along fixed airways during fog or low visibility was given in a paper entitled *Uses of Radio as an Aid to Air Navigation*,⁸ by Dr. J. H. Dellinger, presented at the Winter Convention.

WIRE LINE SYSTEMS FOR BROADCASTING

In the June 1926 report of this committee, mention was made of the fact that long distance wire lines were coming into use for enabling good programs to be made available at a number of widely separated broadcast stations. This use of wire lines in connection with broadcasting has increased tremendously and the circuits regularly in use for this purpose on January 15, 1929 served more than 110 radio broadcasting stations and included more than 28,000 mi. of telephone circuit. In addition, over 40,000 mi. of telegraph circuit were also in use for control purposes.

FREQUENCY CONTROL IN RADIO

With the growth which is occurring in the number of radio channels, especially those operating at the higher frequencies (short waves), the ability to set the channels accurately in the frequency spectrum and to hold them to their assigned frequencies during operation has become of fundamental importance. Substantial contributions have been made during the past year or two in improved methods for accurately measuring frequencies and in the practical working out of the quartz-crystal oscillator control for transmitting stations. Most of the more important broadcast stations of the United States are now crystal-controlled, whereby their frequencies are maintained with an accuracy of the order of ± 50 cycles. Stations not equipped with such control sometimes find difficulty in staying within a ± 500 -cycle limit. The majority of the more important short-wave transmitters of the world are likewise using crystal control but due to the imperfections of the arrangements in practical use, much interference exists between these short-wave channels. Laboratory advances made during the past year

in the crystals themselves, including the manner of cutting them and of controlling their variation with temperature, as well as improvements made in the circuit arrangements for employing them, will reduce this interference as these methods become more generally available in practice.

A frequency meter has been developed which reads radio frequencies directly on an indicating instrument. This operates on a heterodyne principle in which the standard circuit is controlled by a piezoelectric crystal oscillator. The accuracy is 100 cycles in a million.

RAILROAD TRAIN RADIO EQUIPMENT

Further progress has been made in the application of radio communication between front and rear ends of railroad trains. In a recent installation, modulated continuous wave transmission at a wave length slightly over 100 meters is used and reliable communication is obtained. While the main principles employed remain unchanged, much has been done toward solving the design problems involved.

TRANSATLANTIC TELEPHONY

The most outstanding phases of transatlantic telephony during the past year were the very substantial growth which occurred in telephone traffic and the extension of service to all points in Germany, Holland, Belgium, Switzerland, and Spain, and to one city in northern Africa. Certain other important points were reached also, such as Paris, Copenhagen, Stockholm, and Vienna. The extension to Paris was very important, as about 25 per cent of the traffic is to or from Paris as compared to 50 per cent to London and from 5 to 10 per cent to Berlin. On the American side, the service was extended to nine cities in Mexico, seven of the more important cities in Western Canada, and to all points in the provinces of Ontario and Quebec.

To facilitate the operation of the circuit, printing telegraph machines are now used during intervals between telephone calls for the purpose of passing "ticket information" regarding the calls and for transmitting other messages relating to the service.

In June 1928 a second two-way circuit was brought into service. The radio portion of this circuit uses very short waves, 16 to 33 meters in length, as contrasted with the long waves used for the other transatlantic circuit. The circuit is arranged to be used either independently or in combination with the older circuit, and experience has shown that the combination of long and short wave circuits gives a greater over-all reliability than with the same number of facilities operated on either long or short waves. It is expected that the increasing use and further development of transatlantic telephony will require further facilities.

During the year the research engineers of the Bell Telephone Laboratories have perfected a means of making a transatlantic telephone cable. Until now a submarine cable of this length has been impossible as

8. *Ibid.*, p. 563.

current sufficient to carry speech could not be sent by submarine cable such long distances, because the devices which are used on land for amplifying the speech currents, such as loading coils and repeaters, could not be attached to the wire under water. This cable when constructed will not only substantially increase the telephone facilities for transatlantic communication but will also provide a circuit of maximum reliability.

TRANSATLANTIC TELEGRAPHY

One of the accomplishments in the communication field during 1928 was the successful laying of the Bay Roberts-Horta duplex loaded cable by the Western Union Telegraph Company. This cable differs from loaded cables previously laid by that company in that the loading material is Mu-metal instead of permalloy, put on in the shape of wire instead of ribbon as formerly used. In order to permit of successful balancing for duplex operation, the cable is fully loaded only on the mid-section. Towards the ends, the amount of loading material is decreased until the shore ends proper have no loading material whatever. The cable was designed to give a speed of 1000 letters per minute duplex, or 2000 letters per minute simplex, but tests made thus far upon the cable indicate that these speeds may be exceeded.

PRINTING TELEGRAPHY

The expansion in the telephone typewriter service has been marked by the installation of more than 3000 printing telegraph machines during the past year. Special circuits and switching arrangements have been developed for use by the subscribers in interconnecting the lines used with these types of machines. A number of these switching arrangements has been installed to meet the special requirements of customers where a switched typewriter service somewhat similar to that given with telephone instruments associated with private branch exchanges is needed. These arrangements enable a quick communication service to be obtained and at the same time have the advantage of giving a written record of such communications.

Printing telegraph instruments of the same general character as those mentioned in the preceding paragraph are also being used in rapidly increasing numbers by the commercial telegraph companies, about 6000 having been installed during the past year. In this field for the transmission of telegrams the principal application of the machines is on lines connecting main and branch offices of the telegraph company with each other and with customers' establishments. The major switching problem involved is the concentration of numerous lines of this character for efficient traffic handling by a group of central office operators. Equipment recently installed permits the concentration of one hundred or more lines so as to be accessible to any required number of operators.

Excellent progress was made during the year in the joint development by the Teletype Corporation and the

Western Union Telegraph Company of a high-speed ticker capable of operating at 500 characters per minute. Installation of this new ticker and its associated equipment will take place during 1929 in the New York Stock service. The same machine will be used by the Telegraph Company and by the New York Quotation Company, which is the official operating company of the New York Stock Exchange.

In the field of trunk-line message circuits between cities, which are usually operated by high-speed multiplex printing telegraph apparatus, an important development of the past year has been the extension of metallic circuit working. Most earlier attempts have required the use of two line wires for each metallic circuit. In the system now successfully used by the Western Union Telegraph Company, three high-speed metallic circuits are obtained from each group of four-line conductors without carrier frequencies.

FACSIMILE TRANSMISSION

A considerable increase in the use of the telephotography service of the Bell System resulted from commercial arrangements made during the year. Under these arrangements, the leading telegraph companies collect from and deliver to the public photographs, diagrams, and other facsimiles which are transmitted over the telephotograph circuits.

The Westinghouse Electric and Manufacturing Company reports that an apparatus has been developed for facsimile picture transmission which is considerably more rapid than the existing commercial systems. It is expected that this will be available for sale in a comparatively short time.

TELEVISION

What appears to have been the most significant advance in television made during the year was the development of equipment for the transmission of images of outdoor scenes illuminated by sunlight. A public demonstration of this equipment was given at the Bell Telephone Laboratories on July 12, 1928, at which time action scenes, such as a tennis player going through his strokes, were successfully transmitted.

An improved photoelectric cell of greater sensitivity and a more efficient optical system for scanning were employed.

SOUND PICTURES

The year 1928 saw wide extension of sound-picture systems throughout the theaters of the United States, and the equipment of the important studios with recording apparatus for producing both disk and film records. The light-valve method of recording sound on films was introduced commercially, and altogether, during the year about 2000 sound projector equipments were put into use in motion picture theaters in the country. Also improvements in frequency range of recording and reproduction were made during the year, and electrical systems for the accurate speed control of the projector equipment were utilized in the reproduc-

ing systems. Field equipment, as distinct from studio equipment, was developed for recording, as was also portable projector equipment. The first educational sound-picture film, a production of the Bell Telephone Laboratories, made its appearance during the year, developing the principles of carrier-current telephony, particularly modulation and filtering. This film was projected before several scientific and educational audiences.

MUNICIPAL AND PROTECTIVE SIGNALING

There has been a considerable increase in electrical signal devices for traffic control. Synchronous control of such signals along a street or throughout a section appears to be growing in favor. Progress has been made in the application of signals which normally permit a steady flow of traffic along a main thoroughfare

but subject to manual or automatic reversal on the approach of traffic from a side or cross street.

For small fire alarm systems, an improvement of the past year has been the introduction of electrical sirens that can be coded satisfactorily. The various defects of former types have been overcome to a great extent, and further development will lie probably in provisions for emergency power supply to ensure operation even if the public electrical supply should be deranged.

An increase is noted in the use of police signaling systems. The older local battery systems are being converted to central energy operation in some cases. There is also a tendency of banks and other financial institutions to connect their protective circuits and vault alarm systems to the police signal circuits. Some expansion has also taken place in the interurban teletype signaling systems mentioned in last year's report.

Education

ANNUAL REPORT OF COMMITTEE ON EDUCATION*

To the Board of Directors:

The continued rapid increase in scientific knowledge and in the diversity and complexity of the engineering applications and the engineering responsibilities, combine to make the four-year engineering program a less and less adequate preparation for effective engineering work.

This situation is not peculiar to the engineering profession. The medical and the legal professions have been confronted by a similar situation and to meet it they are requiring students aspiring to those professions to remain on the college campus for a period of 6 years, and after that to serve an apprenticeship of 6 months or a year as a law clerk or a medical interne.

The study of engineering education conducted by the S. P. E. E. has disclosed the fact that very few teachers or engineers propose to meet the situation by requiring *all* engineering students to remain upon the college campus for a fifth or sixth year. Before increasing the length of the engineering course for all students, the engineering profession first proposes to try out thoroughly an alternative method.

This alternative method is to encourage the comparatively few graduates of the four-year engineering course who are possessed of the requisite interest, ability, and financial means, to continue in residence by enrolling in the Graduate Schools, and to encourage the majority, who will continue to enter at once upon their engineering apprenticeships, to continue their educational efforts in a more systematic manner and to a more definite end than at present.

Of all the possible educational movements in which the Institute Committee on Education might engage, none seemed to the committee to have greater possibilities of advancing the standards of professional attainment and proficiency than this movement to stimulate interest in the systematic continuation of engineering education after college and to make adequate provision for a program of post-college education.

The full development and realization of the great possibilities of post-college education will require the cooperation of the engineering profession with the industries and the colleges, and it seemed to the committee that it could render its most effective service:

1st, by seeking to bring the thought of the Institute membership to bear upon the possibilities and the

problems of post-college education and upon the responsibilities of the profession relative to this period of training;

2nd, by seeking to stimulate the local Sections to promote this movement by setting to work to canvass or inventory the post-college needs and the educational facilities of their districts and to coordinate the two;

3rd, by seeking to act as a center through which a knowledge of distinctive and effective developments in the field of post-college education may be made known generally.

The views and the aims of the committee have been stated in a brief article entitled *The Post-College Education of Engineers*, which appeared in the April, 1929 issue of the JOURNAL. In this article it is suggested that the local sections, particularly in the industrial centers in which Colleges of Engineering are located, each appoint a Committee on Education. It is suggested that the function of the section committee on education be to canvass the needs and the wishes of the engineers of the district, particularly the younger engineers, and to make these needs and wishes articulate by bringing them to the attention of the college administrations, or the industrial managements, or the engineering authorities in the district in the form of explicit statements such as the following: We have a group of 20 men who will enroll in a course in differential equations, to meet one evening a week for a year, or 15 men who will enroll in a course in advanced circuit theory, or 30 men who will enroll in a course in engineering economics. What provision can be made to meet the needs of these men?

A fully developed program of post-college education will mean a large and important expansion of the work of the colleges of engineering and will play an important part in the development of engineering teachers. This post-college training will compel and will reward a broader and more thorough training than is common in the teaching ranks today. It will afford greater opportunities to determine the adequacy, the relative importance, and the real significance of the principles and the methods taught to undergraduates. It will make teaching attractive to a wider range of engineers by making it possible for men in teaching to have closer contact with engineering practise.

*COMMITTEE ON EDUCATION:

Edward Bennett, Chairman.

E. W. Allen,

J. L. Beaver,

H. W. Buck,

V. Bush,

O. J. Ferguson,

A. B. Gates,

W. B. Hartshorne,

Paul M. Lincoln,

C. E. Magnusson,

W. E. Mitchell,

H. S. Osborne,

A. G. Pierce,

O. S. Ruffner,

W. S. Rugg,

W. E. Wickenden.

Discussion

F. C. Caldwell: Professor Bennett has spoken of the discussions that were held at Columbus last week and has brought out the emphasis that was put on two grades of education not included in the ordinary college curriculum. The statement was made by Dr. Wickenden in his report on the investigations made

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

under the auspices of the Society for the Promotion of Engineering Education that not much fault had been found with the four-year college course as it is now being given. Some minor changes were suggested, but nothing of great importance. It was suggested, however, that there are two other levels of education that needed cultivation. Professor Bennett has emphasized one of these, the graduate level. The other is also interesting. It was stated that in Europe the so-called technical schools were sending into the industry three or four times as many men as the universities, whereas, in this country, the number supplied by such institutions as Pratt Institute and Wentworth Institute was only a fraction of the number supplied by the colleges. I foresee that we are going to find in the coming years a greater and greater shortage of college trained electrical engineers. We may look for no considerable increase and possibly for a decrease in the number of electrical graduates, unless something happens to change the present trend.

There is no notable growth in the total number of students going into the engineering colleges. The selection of their curricula by most high-school boys has not much rational basis. During recent years, the electrical engineering courses have had more than their share of the students. This has doubtless been partially due to the popularity of radio among boys of high-school age; this popularity, however, is probably waning somewhat.

On the other hand, there is the great development of aeronautics; most high-school boys want to fly, and many are looking to the opportunities for training in aeronautics given in the universities.

The mechanical engineering departments of the universities are developing their courses along those lines and during the next few years there is likely to be a trend away from electrical and toward mechanical engineering; first, because of the decreasing interest in radio on the part of the boys, and, second, because of the increasing interest in aeronautics. This may develop a rather

critical situation for the electrical industry. About a third of the students who enter the engineering colleges graduate. The other two-thirds fall by the way, either because they are not able to keep up the pace or for financial or other reasons.

The problem is to find some way by which those men who drop out now can be given a training more effective because better adapted to their mental capacity, in other words, to do just what is being done in Europe. These men must be provided with a less theoretical training, which would also suit better some of the men who do now graduate. Some of these do not get much advantage out of the more theoretical work of the upper years. They barely get by and have very hazy ideas of what they have studied.

If industry can realize this situation, can create a demand for men with a lower grade of training and can bring about or help to bring about the organization of schools of suitable grade, then we may be able to make the supply of trained electrical engineers go around. Perhaps the universities also may be induced to give training of this lower grade.

Charles Ficklenburg: Speaking from a manufacturing standpoint, one of the difficulties that we have found in engineering graduates is the lack of mechanical engineering graduates who wish to go into electrical manufacturing. We find that the structures for carrying the electrical parts require a very high degree of mechanical knowledge and we find it increasingly difficult to obtain from the colleges graduates who have the necessary electrical knowledge as well as the necessary mechanical knowledge.

We can put down very easily the electrical characteristics; we can solve those electric characteristics, but when it comes to mechanical structure to carry the electrical conductors, the magnetic circuit and the like, we are woefully weak.

So I should like to make a plea to the Committee on Education and through them to the colleges that more stress be placed upon teaching students the mechanical features and limitations, rather than purely theoretical electrical subjects.

Electrical Machinery

ANNUAL REPORT OF COMMITTEE ON ELECTRICAL MACHINERY*

To the Board of Directors:

The Committee on Electrical Machinery has functioned under an organization similar to that of last year, that is with subcommittees commissioned to handle all the matters of a particular type of equipment that properly belong to this committee. These subcommittees were as follows:

Direct-Current Machinery, Mr. H. L. Zabriskie, Chairman; Induction Motors, Mr. P. L. Alger, Chairman; Rectifiers, Mr. B. G. Jamieson, Chairman; Synchronous Machinery, Mr. S. L. Henderson, Chairman; Transformers, Mr. W. M. Dann, Chairman.

A special subcommittee with Mr. C. M. Gilt as chairman was commissioned with the preparation of the annual report.

The proposed standards of the I. E. C. on "Rating of Electrical Machinery" were referred to the committee for advice. There was a number of minor differences between them and those of the Institute, which the committee believed could be readily adjusted without violating established principles of standards of either European or American practise. However, a few features differed so fundamentally from accepted American practise that the committee recommended strongly against approval of them. Among the most important items to which objections were raised were the higher temperature rise permitted for transformers, the generally lower temperature rise allowed for commutators, and the permissibility of tolerance in those guarantees of performance, such as efficiencies, that are accepted in this country as limits rather than calculated expectations.

The committee has continued its work associated with the preparation of material for recommendations for new standards or modification of existing standards. Included in the recommended modifications of the Transformer Standards was an appendix designed to outline operation by temperature rather than rating. These reduce the hot spot temperature from 105 deg. to 95 deg. except when operating according to name plate rating with ambients above 30 deg. and do not permit an increase in output beyond that permissible at 0 deg. cent.

The recommendations for Standards for Constant Current Transformers have been practically completed

and it is expected that these will be presented for further action shortly.

It has become evident that some equipment and engine builders have been somewhat skeptical of the value of the conventional efficiencies of rotating equipment, particularly those of low-speed engine type generators and motors in which windage and bearing friction are excluded, and have been assuming input-output efficiencies much below those actually obtained. Steps have been initiated to clarify this situation and plans are being formed to include an arbitrary but small allowance for such of these losses as may be properly included, when they are not actually measured.

The increase in use of enclosed ventilated rotating equipment with self contained or separate fans has indicated the necessity for more satisfactory rules governing the allocation of ventilating losses. The problem has been accentuated by electrical ship propulsion in which the losses in the external ducts may be a large or even major portion of the ventilating losses. An endeavor is being made to formulate rules for the allocation of these losses that will be basically sound and readily applicable.

At present there are no Standards for a-c. commutator motors and their importance, both in the single-phase and multi-phase types, has grown to the point where the committee has undertaken the preparation of material for standards. Studies have been conducted in the stray load losses of induction motors so that a reasonable allowance may be included when not determined by test. Other modifications of the present Standards are under consideration.

Mercury arc rectifiers have been actively studied and records of performance and characteristics assembled. Bases of rating have been somewhat uncertain, and it has become evident that the present Standards for Transformers are not entirely applicable to transformers used with rectifiers, due particularly to the non-sinusoidal current and voltage waves imposed by the rectifier. Ground work for the preparation of Standards has been well laid.

It has been felt that there is need for a well recognized test code in the electrical field as has been established in some other fields. Each of the manufacturers has his own test code, and some of the users have developed or adopted test procedures, but there is no common or generally recognized code. The committee has therefore recommended that such a code be prepared and issued by the Institute.

At the Winter Convention, two sessions were sponsored by the committee. One session was devoted to the induction motor, including the capacitor motor, which has recently come into prominence due to the requirements for high power factor low starting current

*COMMITTEE ON ELECTRICAL MACHINERY:

W. J. Foster, Chairman,		
E. B. Paxton, Secretary,		
P. L. Alger,	B. G. Jamieson,	O. K. Marti,
B. L. Barns,	J. Allen Johnson,	V. M. Montsinger,
A. B. Cooper,	A. H. Kehoe,	F. D. Newbury,
W. M. Dann,	C. W. Kincaid,	J. M. Oliver,
C. M. Gilt,	H. C. Louis,	A. M. Rossman,
W. S. Gorsuch,	A. M. MacOutcheon,	R. B. Williamson,
Stuart L. Henderson,		H. L. Zabriskie.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

single-phase motors for household devices. At the other session the following papers were presented. *Insulation Tests on Electrical Machinery before and after Being Placed in Service; Effect of Transient Voltages on Power Transformer Design; Transient Analysis of A-C. Machines; Two-Reaction Theories of Synchronous Machines; Influence of Temperature on Large Commutator Operation.*

No radical departure in size or design of apparatus has been evident during the last year, but there has been a gradual upward tendency in ratings and effi-

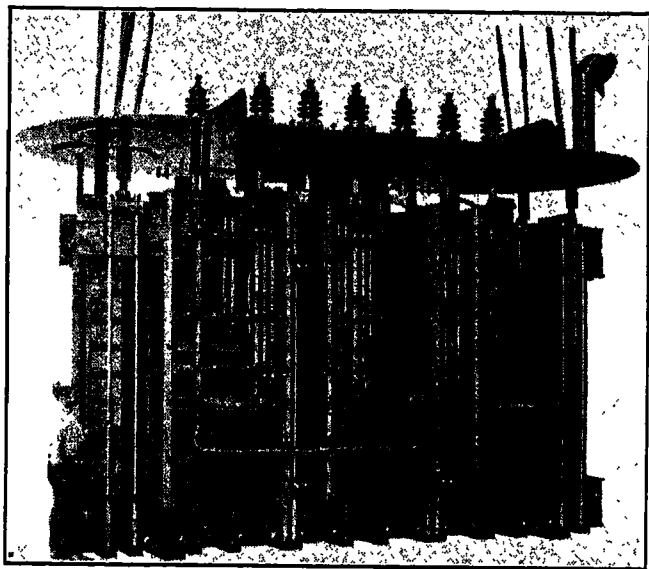


FIG. 1—LOW-VOLTAGE SIDE OF CORE AND COILS OF 83,333-KV-A. AUTO-TRANSFORMER, 24,500/12,000 VOLTS, THREE-PHASE, 25-CYCLES

For the Buffalo General Electric Company

ciencies. Refinements in design and improvements in materials have increased the output per pound of material, usually accompanied by lower losses. In some lines factory methods are rapidly being changed by the substitution of structural and rolled steel parts for castings, and it is expected that these changes will be more obviously reflected in designs as advantageous modifications become evident. While the maximum nominal operating voltage has not been extended beyond 220 kv., the upward trend of voltage has been evident in large equipment, both in the static and rotating fields. More specifically, some of the trends and typical examples of recent developments are outlined in the following paragraphs.

TRANSFORMERS

Transformers, while apparently well stabilized in types of construction, have increased in size, and their already small margin of losses has been further reduced. Efficiencies have been obtained as high as 99.71 per cent at three-quarters load in a 45,833-kv-a. output, 60-cycle, single-phase, self-cooled auto transformer having a voltage ratio of 15,940 to 7970 and 99.54 per cent at half load in a 40,000-kv-a., three-phase, 60-cycle self-cooled two-winding transformer having a ratio of 29,000/13,800.

The manufacturers have recently extended their special studies and investigations in high voltage and

high voltage disturbances. As an example of work being done along these lines, the testing facilities of the General Electric Company at Pittsfield have been increased to include a "lightning generator" capable of delivering 5,000,000 volts, which is higher than any voltage so far measured on any transmission line, and the Westinghouse laboratory is able to produce over 3,000,000 volts.

Investigations of the manufacturers into the effects of distribution of impulse voltages on transformer windings have been carried on actively by means of klydonographs, cathode ray oscillographs, and surge voltage recorders. These indicate that the distribution of the voltage varies with the frequency and the physical arrangement of the transformer and lightning impulses and high frequencies may build up very high local voltages within the transformer windings.

To eliminate uneven distribution and high local stresses, the General Electric Company has developed and put into service a new type of transformer which has been called "non-resonating." Published tests indicate that in the "non-resonating" transformer the voltage distribution is approximately uniform and the same for high frequencies and impulses as it is for operating frequencies. These results are obtained by the use of special shields connected to the line terminals but external to the windings, so that the necessary charging current can be supplied directly to the various coils rather than indirectly through the line end coils.

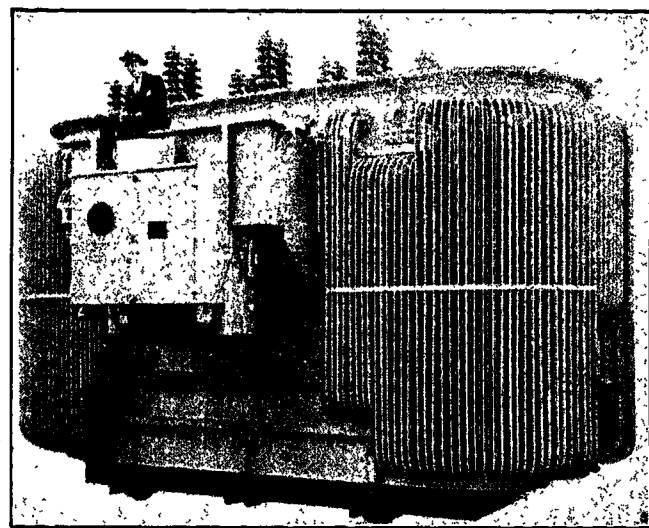


FIG. 2—SEPARATE REGULATING TRANSFORMER FOR 11 PER CENT REGULATION ON A 50,000-KV-A., THREE-PHASE, 24,000-VOLT CIRCUIT

The first of the "non-resonating" transformers have been in operation about two years.

The studies of the Westinghouse Company have led them to believe that a very satisfactory distribution of voltage is obtained throughout the windings of their transformers when exposed to lightning conditions and have increased their confidence in the reliability of their transformers at such times.

The use of load ratio control which has been previously described, has materially increased and the manufacturers have simplified their design and reduced

the dimensions of equipment so that it may now be secured on the transformer tanks and requires very little more floor space than that necessitated by radiators. In this equipment the voltage ratio may be changed under load and the same type of switching equipment in conjunction with regulating transformer windings may be used to obtain phase angle control where necessary.

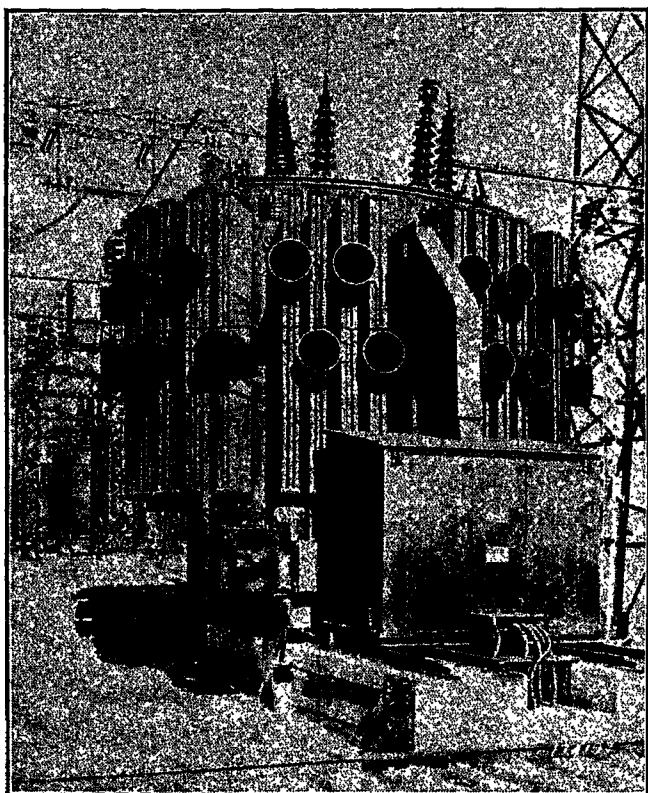


FIG. 3—43,333-KV-A. POWER TRANSFORMER—60 CYCLES, SINGLE-PHASE 220/69/13.2 Kv. WITH LOAD RATIO CONTROL FOR THE 69-KV. WINDING AND AUXILIARY UNIT TYPE AIR-BLAST EQUIPMENT

For the Plymouth Meeting Station

Forced air ventilation, supplementing self-cooling, has been used in a number of installations. This is particularly effective in large self-cooled units in decreasing the radiator surface required for maximum ratings while still permitting operation of the self-cooled unit without the blower losses at moderate ratings. Two types of equipment are furnished, one of which consists of a single blower piped to all the radiators of the transformer, and the other of small individual blowers and housings that are added, one to each radiator.

Three-winding transformers have continued in popularity in the large capacity units, and the Westinghouse Electric and Manufacturing Company reports that nearly half the large power transformers ordered from their company in 1928, were of the three-winding type.

Typical of the most notable installations of large units, may be mentioned the following:

An 83,333-kv-a. output, three-phase, 25-cycle water-cooled auto-transformer having an equivalent transformer capacity of 49,200 kv-a. was installed by the Buffalo General Electric Company. The unit was supplied by the General Electric Company and probably concentrates in one unit the largest kv-a. output so far undertaken in transformer construction. The

high-voltage winding consists of two circuits, each of which is to be connected to a separate section of the station bus. The windings are so arranged that a short circuit on one winding tends to raise the voltage of the other, which aids in maintaining the voltage of the other bus section.

The largest self-cooled transformer reported consists of 40,000 kv-a., three-phase, 60-cycle, transformers supplied to the United Electric Light and Power Company of New York by the Westinghouse Company.

Six single-phase, 15,000-kv-a. water cooled 25-cycle, three-winding transformers with a voltage ratio of 220/110/132 kv. with both low-voltage windings of full capacity, are probably physically the largest 25-cycle units yet supplied and weigh over 175 tons each. Tap changing under load with $7\frac{1}{2}$ per cent buck and boost was furnished for the 110-kv-a. windings. They were supplied to the Hydro-Electric Power Commission of Ontario by the Canadian Westinghouse Company.

Two banks of 60-cycle single-phase transformers having a self-cooled rating of 33,333 kv-a. per transformer and a rating of 43,333-kv-a. per unit with auxiliary air blasts were installed by the Philadelphia Electric Company in the Plymouth Meeting Substation. They are Westinghouse three-winding transformers with voltage rating of 220 kv. star *H. V.*, 69 kv. star *M. V.*, 13.2 kv. delta *L. V.* They are equipped with the older type of load ratio control to give 15 per cent regulation in six $2\frac{1}{2}$ per cent steps in the 69-kv. winding.

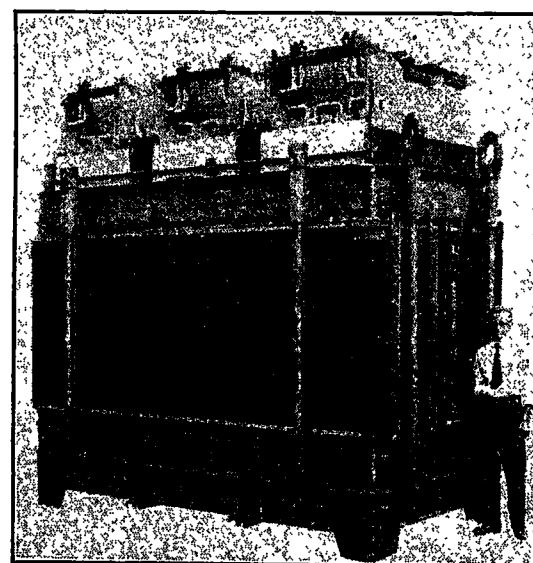


FIG. 4—CORE AND COILS OF A 40,000-KV-A. SELF-COOLED POWER TRANSFORMER—THREE-PHASE, 60 CYCLES, 29/13.8 Kv. FOR USE WITH A FREQUENCY-CHANGER SET

At the United Electric Light and Power Company

Two three-phase air-blast transformers supplied the New York Edison Company by the General Electric Company have extended the rating of air blast units so far produced. Each is rated 18,500-kv-a., 25-cycle, 11800/3300/440 volts, and will operate in conjunction with a 40,000-kw. induction synchronous frequency-changer set.

Attention has been given to the problem of low cost, small power supply from high-voltage lines, and a

standard "substation" has been made available for use on 66,000-volt grounded neutral systems with a capacity of 15 to 50 kv-a. single-phase. The unit consists of an over insulated single bushing transformer with a combined disconnecting switch fusible cut-out and current limiting resistor for the high-tension winding. Metering equipment, cutouts, and arrester are included in the 2300-volt connections.

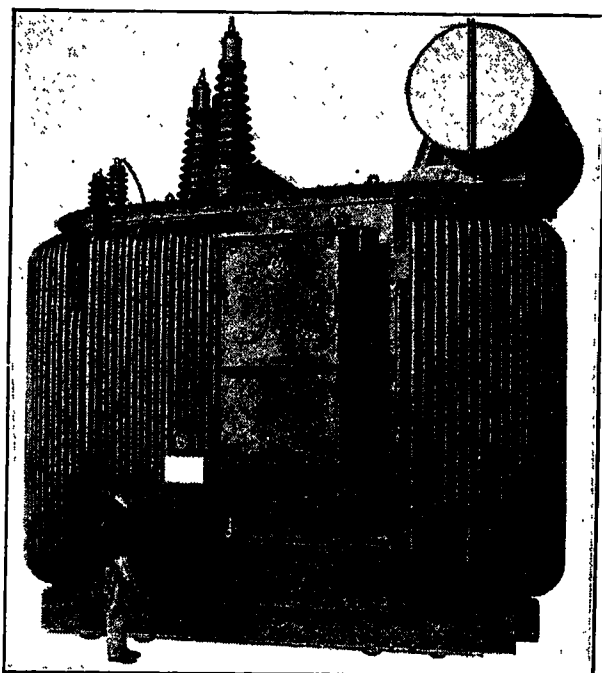


FIG. 5—20,833-KV-A. POWER TRANSFORMER—60 CYCLES, THREE-PHASE, 120/120 KV. SHOWING LOAD-RATIO CONTROL SIDE
For the Detroit Edison Co.

HIGH-VOLTAGE METERING

The Philadelphia Electric Company has placed in operation metering equipment for measuring the power supply at full voltage on the 220-kv. line connection with the Pennsylvania Power and Lighting Company. The equipment consists of three units each containing single-phase current and potential transformers connected between line and grounded neutral. Similar installation has been made by the Appalachian Electric Power Company consisting of two units of current and potential transformers. The potential transformers are designed for use on a 220-kv. three-phase system with a neutral either free or grounded. Both of the above equipments were furnished by the Westinghouse Company.

REGULATORS

The Westinghouse Company has brought out a new design of outdoor type regulator aimed to make the installation of these units more convenient. An outdoor covering has been provided which can be removed complete by unscrewing the eyebolt. Doors are provided for giving access to the motor and other auxiliaries, with a window in front for viewing the position indicator. A centralized lubricating station is included with alemite fittings to lubricate all bearing surfaces not immersed in oil. The weatherproof box containing the relays and control auxiliaries and a neutral return and manual return switch is mounted on the front of

the tank. All six power leads are carried up through the cover into a separate compartment at the rear of the hood, where the instrument transformers are connected.

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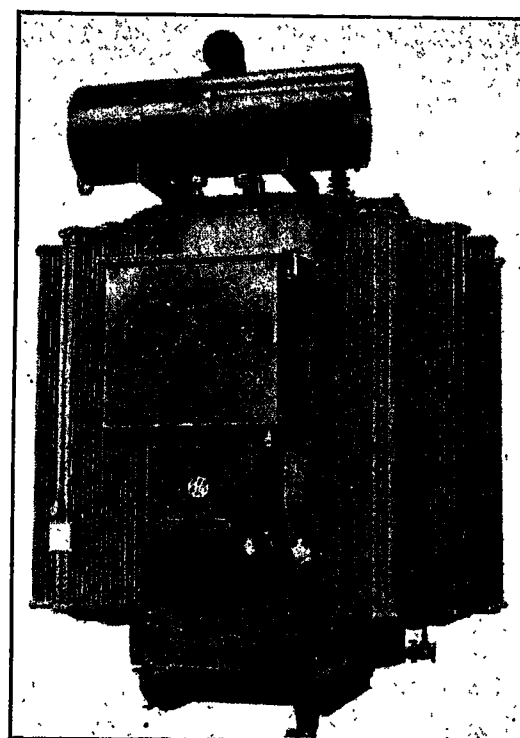


FIG. 6—20,000-KV-A. POWER TRANSFORMER—60 CYCLES, THREE-PHASE, 41,830/72,450 VOLTS. CONTACTOR AND MECHANISM HOUSING SIDE

For the Philadelphia Electric Company

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SYNCHRONOUS MACHINES

The tendency toward larger machines has continued in the field of water wheel generators, but there has been no increase in size of single or multiple shaft turbine generators beyond those previously reported.

The use of fabricated machines has been considerably extended and the more important parts such as frames, bearing brackets, and rotor spiders of practically all machines are built up from steel plates and rolled members. Some welded bearing pedestals have been built, but the use of cast pedestals still predominates. Castings still hold their own for small standard machines.

Experience is being accumulated in the use of quick response excitation and speeds of increase in exciter

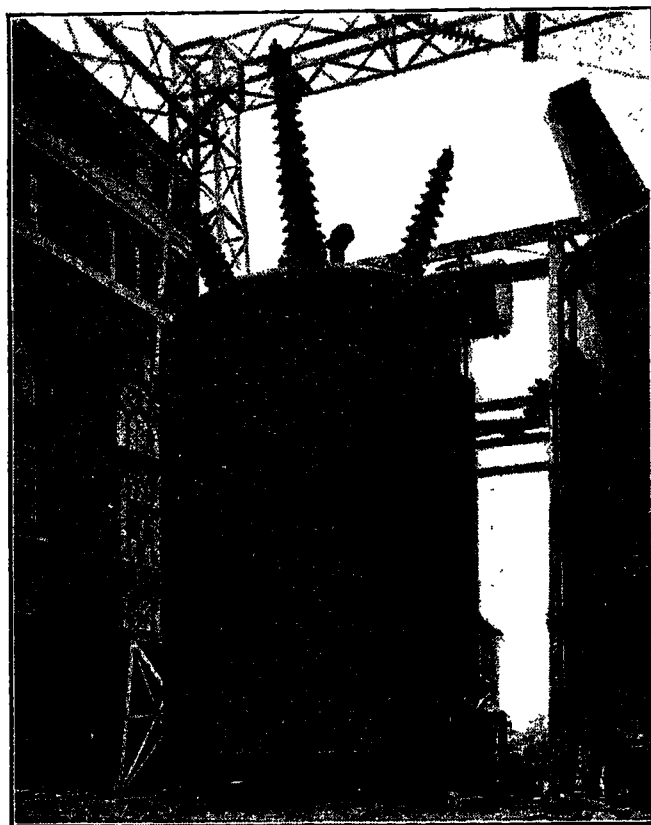


FIG. 7—15,000-KV-A. POWER TRANSFORMER—25 CYCLES, SINGLE-PHASE, 120/65/13.2 KV. ALL WINDINGS FULL CAPACITY

voltage are now available which are considerably in excess of those required for most operating requirements.

More operating experience has been obtained with hydrogen cooled condensers. This type of machine is particularly adaptable to hydrogen cooling, as the bearings can be placed inside the housing, thereby eliminating the difficult problem of sealing the shaft against leakage. The application of this kind of cooling to many a-c. machines has proved practical, but the extent of its use depends on economic considerations. The increase in cost for the enclosures and hydrogen equipment must be balanced against the reduced losses and probable longer insulation life. In many cases a high capitalization of losses will justify the extra cost, but there are some classes of machines, with the more complicated mechanical structures, to which this system of cooling is not yet applicable.

The design of high-voltage machines has been advanced this year, and several generators to operate at

22,000 volts have been built by the General Electric Company. The Westinghouse Company is now building a 75,000-kv-a. 23,000-volt generator. This has been made possible by refinements in manufacture and care in application of existing insulating materials, rather

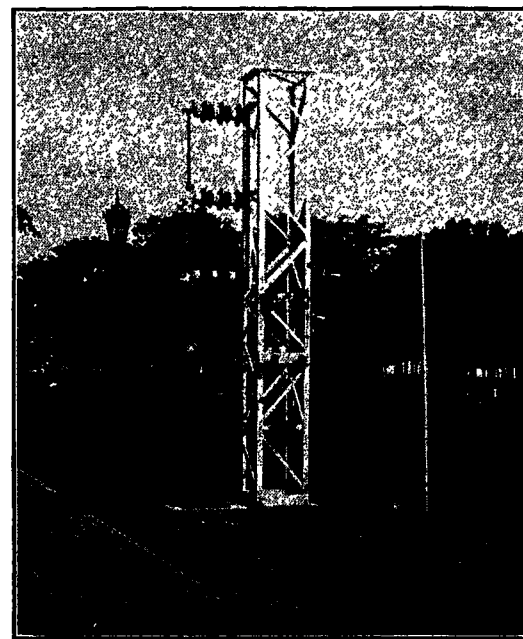


FIG. 8—50-KV-A. HIGH-VOLTAGE TRANSFORMER INSTALLATION FOR RURAL SERVICE 66000/2300 VOLTS

than through the development of new types of insulation. The manufacturers feel that the building of machines for these voltages has reached a stage where their use is a question only of the balance of cost against operating advantages.

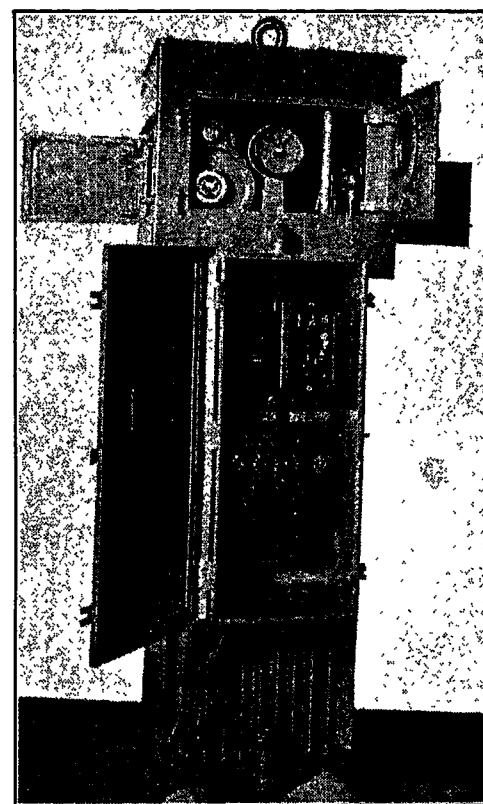


FIG. 9—NEW OUTDOOR TYPE INDUCTION REGULATOR

The Parsons Company in England has designed and built a 25,000-kw., 3000-rev., 33,000-volt generator of great interest by reason of the way in which the problem of insulating for such high voltage was solved. The conductors in the several slots are concentric tubes with simply the innermost insulated for the terminal

voltage. The outermost has a small amount of insulation and stands adjacent to the neutral. This generator is reported to be operating satisfactorily in the Brimsdown Power Station, London.

The scheme of using two independent parallel windings has been applied by the General Electric Company to two large alternators. This allows the two windings to be connected to adjacent bus sections and the reactance between the windings is available to perform the duty of reactors between bus sections. On certain installations a material saving in switching equipment can be made in this way.

A great deal of progress has been made in designing large machines of all classes to operate at speeds higher than were formerly thought possible.

HYDRAULIC GENERATORS

Four water wheel generators, larger than any yet built, were ordered from the General Electric Company by

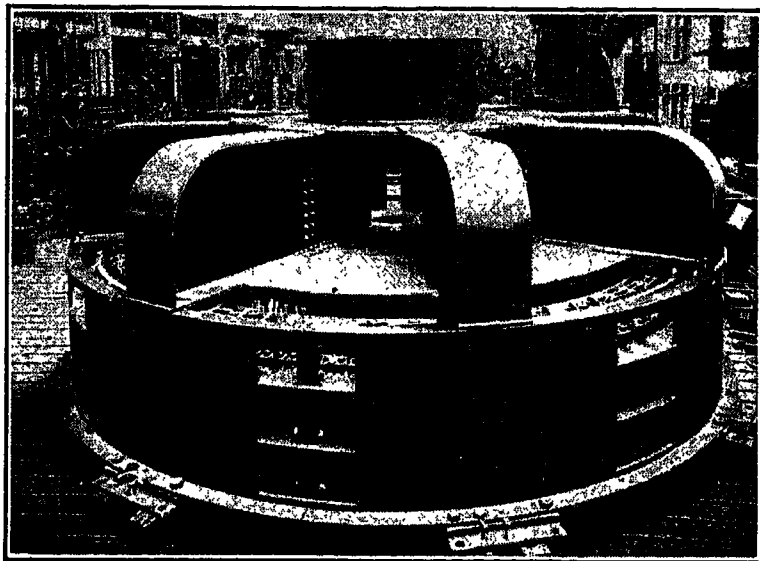


FIG. 10—FABRICATED STATOR FRAME AND UPPER BEARING BRACKET FOR 33,000-KV-A. VERTICAL WATER-WHEEL GENERATOR, ASSEMBLY INCOMPLETE

the Dnieprostroy Hydroelectric Development of Russia. These machines will deliver 77,500-kv-a., 3-phase, 50-cycle, 13,800-volt power at 88.2 rev. per min. Fabricated construction will be used in all principal parts such as frame, upper and lower bearing brackets, and rotor spiders.

The following list comprises the more important machines ordered or installed during the past year.

Purchaser	No.	Kv-a.	Speed	Manufacturer
Dnieprostroy Hydro-electric dev.....	4	77,500	88.2	G. E.
Lexington Power Co.....	4	40,625	138	West.
Phila. Elect. Co.....	4	40,000	81.8	G. E.
	3	40,000	81.8	West.
New England Power Co....	4	39,000	138	West.
Brazilian Hydroelec.....	1	33,000	125	G. E.
Southern Calif. Edison....	1	35,000	375/450	G. E.
Alabama Power Co.....	2	29,000	100	West.
Norwood Electric Co.....	2	27,500	90	A. C.
City of Los Angeles.....	1	25,000 (Hor)	143	A. C.
Montana Power Co.....	2	25,000	81.8	West.
Norwood Electric Co.....	1	22,500	75	A. C.

Many of the above units have high-speed excitation systems to provide greater stability during system disturbances.

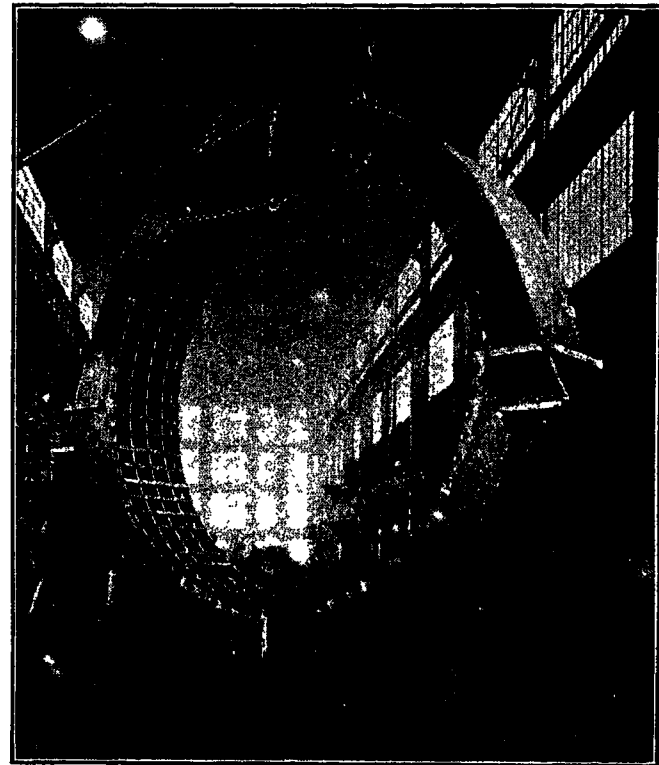


FIG. 11—25,000-KV-A., 143-REV. PER MIN., 50-CYCLE HORIZONTAL WATER-WHEEL GENERATOR WITH WELDED PLANT STEEL YOKE

For the City of Los Angeles

The vertical Westinghouse and Allis-Chalmers units are of the so-called "umbrella" or "overhung" type, with guide and thrust bearings located together under the generator rotor. In this way, the guide bearing is

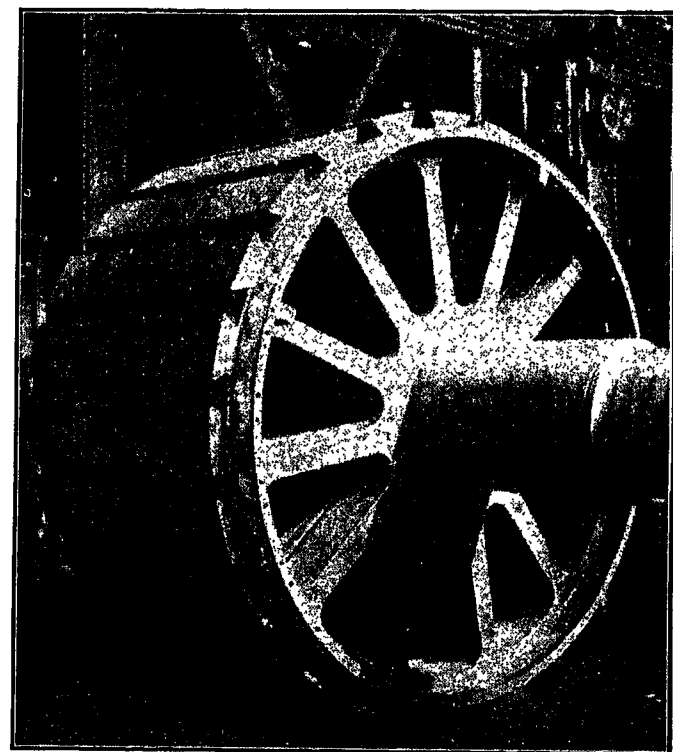


FIG. 12—ROTOR SPIDER OF FABRICATED STEEL PLATE CONSTRUCTION FOR 12,500-KV-A. GENERATOR FOR FREQUENCY CHANGER

brought nearer to the center of gravity and the necessity for an oil circulating system is eliminated. This scheme is especially suited to machines whose diameter is large compared to the height.

The Conowingo units have been installed since last spring. Tests on the General Electric units showed an efficiency of 98 per cent at unity power factor and full load.

The generators for the Brazil Hydroelectric Company

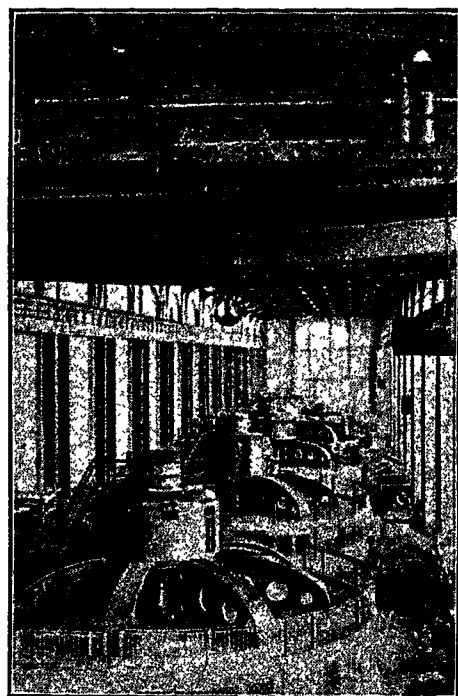


FIG. 13—40,000-Kw., 81.8-REV. PER MIN. GENERATORS AT THE CONOWINGO DEVELOPMENT

were the largest ever built for a foreign customer prior to the order for the 77,500-kv-a. machines for Russia.

The 33,000-kv-a. machine for the Southern California Edison Company is of unusual design as it is rated at 375 rev. per min., 50 cycles but can be run at 450 rev.

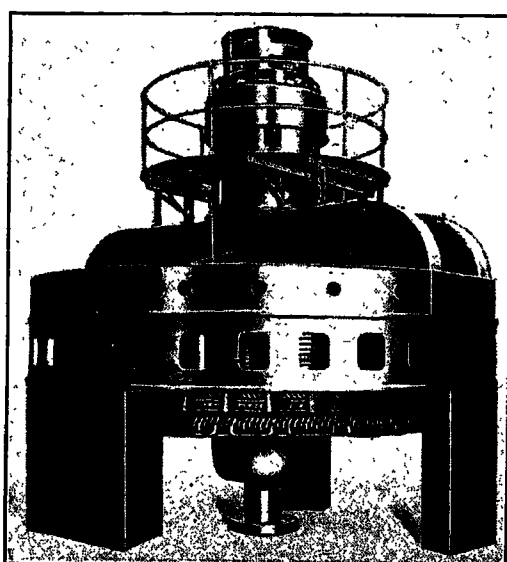


FIG. 14—7500-Kv-a., 225-REV. PER MIN. VERTICAL WATER-WHEEL GENERATOR

per min., 60 cycles. Its stability was increased by making the short circuit ratio higher than usual.

The Westinghouse Company has brought out a new line of small generators, using structural steel parts. The line includes rating from 62.5 kv-a. to 3000 kv-a. with speeds of 100 to 400 rev. per min. The upper and lower bearing brackets, together with the rotor spiders on the slow speed machines, are fabricated.

STEAM TURBINE GENERATORS

There were no orders placed this year for any exceptionally large units, either single shaft or compound. A number of orders was received for machines ranging from 60,000 to 75,000 kv-a.

The use of fabricated structure has been extended by all the manufacturers. Some of the machines have been so designed that a change to hydrogen cooling can be accomplished if it should be found desirable.

Several of the large units mentioned in last year's reports have been or are being installed and some of them are in operation. Among these are the following:

Purchaser	Kv-a.	Speed	Voltage	Shaft	Manufacturer
State Line Generating Co.	235,000	1800	22,000	3	G. E.
United Elec. Lt. & Pr. Co.	188,400	1800	13,800	2	West.
United Elec. Lt. & Pr. Co.	188,250	{ LP 1200 HP 1800 }	13,800	2	A. B. B.
Amer. Gas & Elec. Co.	187,000	1800	11,000	3	G. E.
N. Y. Edison Co..	160,000	1500	11,400	1	G. E.
Brooklyn Edison Co.	137,500	1800	13,800	2	West.
So. Calif Edison Co.	100,000	1500	16,500	1	G. E.
Union El. Lt. & Pr. Co.	83,333	1800	13,800	1	G. E.

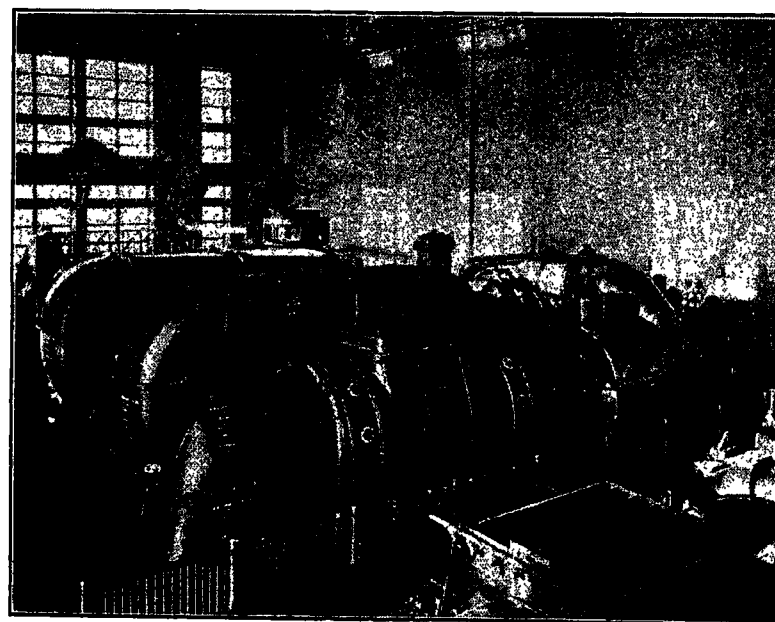


FIG. 15—160,000-Kw. CROSS-COMPOUND TURBO GENERATOR AT HELL GATE

The first 61,765-kv-a. 22,000-volt generator of the Super Power Co. of Illinois at Powerton, has been in operation since August 1928 and the company states that its operation has been entirely satisfactory so far.

The General Electric Co. has built or is building several 12,500-kw., 3600 rev., generators for high-pressure (1200-lb.) turbines. Most of them are 0.8-power factor or 15,625-kv-a. machines. Two generators for unity power-factor operation will be mounted on top of the respective main 1800 rev. generators.

Westinghouse has built a 12,500-kv-a. 3600-rev. per min. machine with self contained fans of novel design. These fans have a double entrance which is said to increase their efficiency materially.

A 7500-kv-a. turbo generator with hydrogen cooling has been placed in experimental operation at the Westinghouse plant. The tests indicate a 25 per cent increase in rating for the same temperature rise above that obtained when operating in air.

SYNCHRONOUS MOTORS

The design of synchronous motors has been considerably advanced, particularly in securing higher



FIG. 16—160,000-Kw. CROSS-COMPOUND TURBO GENERATOR AT HELL GATE

efficiencies and better torque characteristics. The latter are being selected to fit particular applications as more data become available on the starting and operating requirements.

There has been a considerable increase in the use of synchronous motors for the following class of equipment:

Air and ammonia compressors
Tube mills

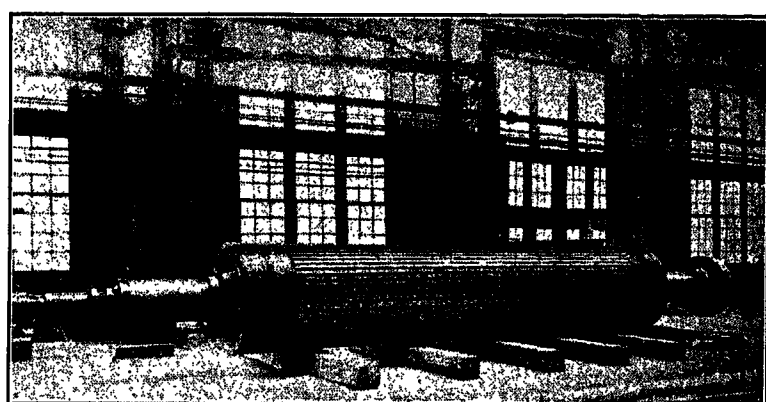


FIG. 17—ROTOR OF 160,000-Kw. SINGLE-SHAFT TURBINE GENERATOR, WEIGHT 261,000 LB.

Ball mills
Vacuum pumps
Water pumps
Pulp grinders
Rubber mills
Steel mills
Jordan engines

The Westinghouse Elec. & Mfg. Company has built two 1000-hp., 180-rev. per min. high-torque motors for

cement mill drive. These machines are of salient pole construction but have polyphase damper windings connected through slip rings to external resistors for starting in the same manner as a slip ring induction motor.

Fig. 20 shows a 5000-hp., 82-rev. per min. synchronous motor for steel mill drive by Westinghouse. This is one of the largest horizontal machines built with fabricated construction.

The first two speed motors with 2 to 1 speed ratio for compressor drive have been placed in operation. These motors have been previously described by the General Electric Company.

SHIP PROPULSION SYNCHRONOUS MOTORS

During the year, the S. S. *Virginia* was placed in service and work started on the S. S. *Pennsylvania*. These vessels will ply between New York and San Francisco at a speed of 18 knots. They have a displacement of a little over 30,000 tons and are propelled by two 8500-hp., 120-rev. per min., 4000-volt syn-



FIG. 18—94,000-Kw. TANDEM COMPOUND TURBINE GENERATOR AT LONG BEACH

chronous motors. Work was begun on two 6300-hp., 120-rev. per min., 3000-volt motors for a Grace Liner, and on four 8000-hp., 143-rev. per min., 3150-volt motors for two Ward Liners. All of these ships are motored with General Electric Company equipment.

SYNCHRONOUS CONDENSERS

No outstandingly large condensers have been ordered during the past year, but much progress has been made in reducing losses, increasing speeds, quickening excitation, and applying hydrogen cooling to commercial machines.

The Westinghouse Elec. & Mfg. Co. has built two 30,000-kv-a. condensers for the Philadelphia Electric Company. These are the largest units so far constructed for 720 rev. per min.

The General Electric Company furnished three units of this size to the same company, the speed being 600 rev. per min. All of these machines are equipped with super-excitation as it was believed of the utmost importance that the system voltage be maintained at a high value during disturbances. The exciters are

designed for a rate of rise of 6000 volts per second with a ceiling voltage of about 950 volts.

The Consumers Power Company has purchased a standard 30,000 kv-a. unit from the Westinghouse Elec. & Mfg. Company.

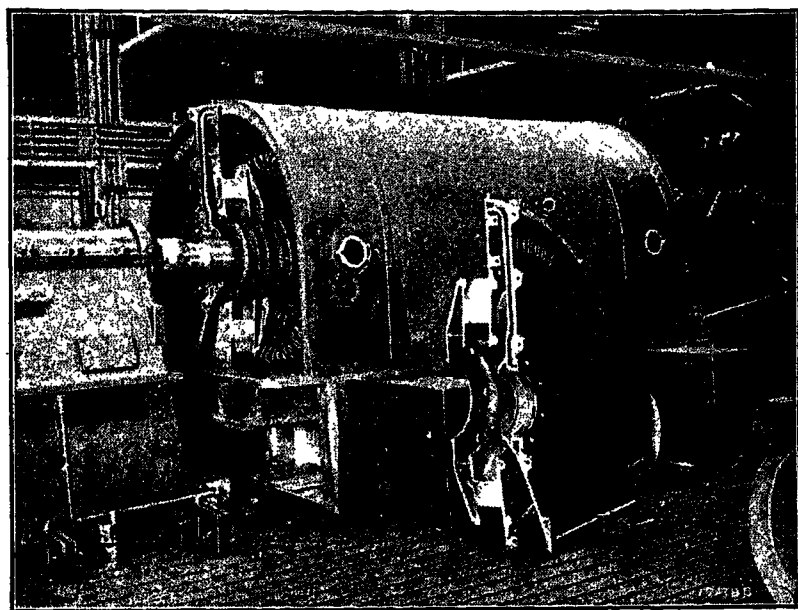


FIG. 19—DOUBLE-ENTRANCE FAN ON A 12,500-KV-A. TURBINE GENERATOR

This company has built two 15,000-kv-a. 900-rev. per min. condensers, this being an advance over the 10,000-kv-a. unit which formerly held the record at this speed.

The first commercial application of hydrogen cooling for electrical machinery was made on a G. E. 12,500-

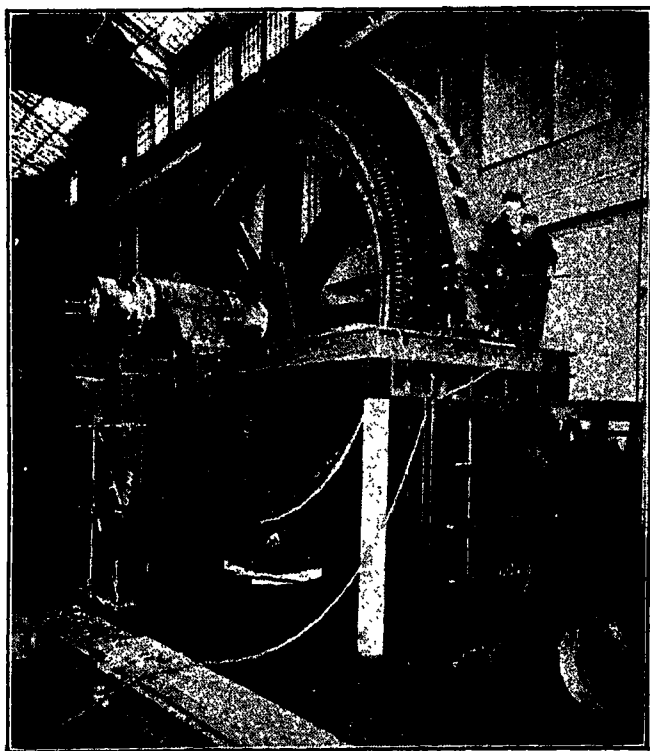


FIG. 20—5000-HP., 82-REV. PER MIN. SYNCHRONOUS MOTOR WITH FABRICATED STRUCTURE

kv-a. outdoor synchronous condenser, located at the Pawtucket substation of the New England Power Company. A larger unit of similar design, rated 20,000 kv-a., is in operation at the Turner Substation of the Appalachian Electric Power Company. The performance of both of these machines during their

few months of operation has been very satisfactory. In addition to reducing the losses and increasing the rating, it is believed that hydrogen cooling also increases the insulation life, reduces the windage noise, and decreases the fire risk.

TEST SETS

During the past year the Canadian General Electric Company has put into operation a new test set for testing large transformers. The set consists of two 7500-kv-a. generators driven by a 2000-hp. d-c. motor. The generators are designed for 3-phase operation or single-phase operation at a capacity of about 70 per cent of the three-phase rating. By means of re-connection and varying the excitation, practically the full kv-a. capacity is available through a voltage range from 1100 to 7600. The generators are wound for either 6 or 12 poles so that the set may deliver the

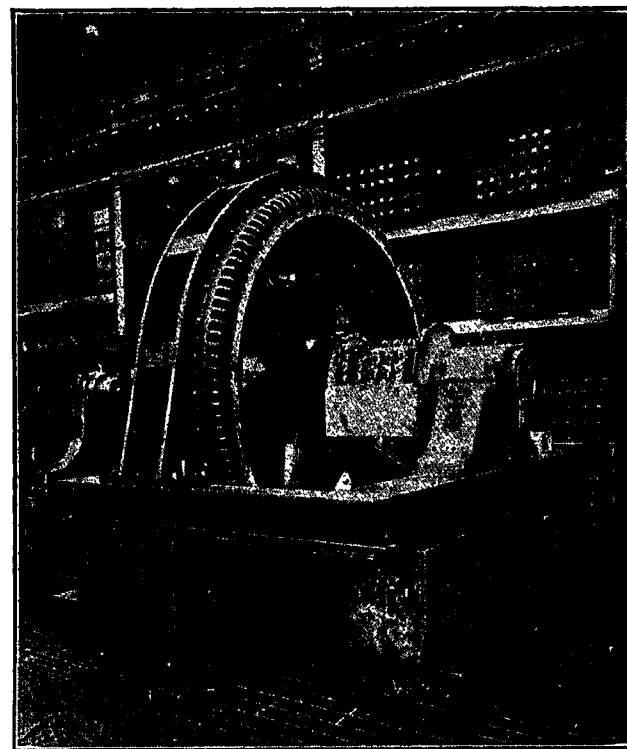


FIG. 21—1000-HP., 180-REV. PER MIN. SYNCHRONOUS MOTOR WITH POLYPHASE DAMPER WINDINGS IN THE POLE FACES AND EXTERNAL STARTING RESISTORS

commercial frequencies used in Canada of 25, 30, 50, 60, $62\frac{1}{2}$, and $66\frac{2}{3}$ cycles.

CONVERTERS

The Allis Chalmers Company has built several large 60-cycle, 3000-kw., 360-rev. per min. railway converters for the City of Philadelphia. These units commutate peak loads of $2\frac{1}{2}$ times nominal rating.

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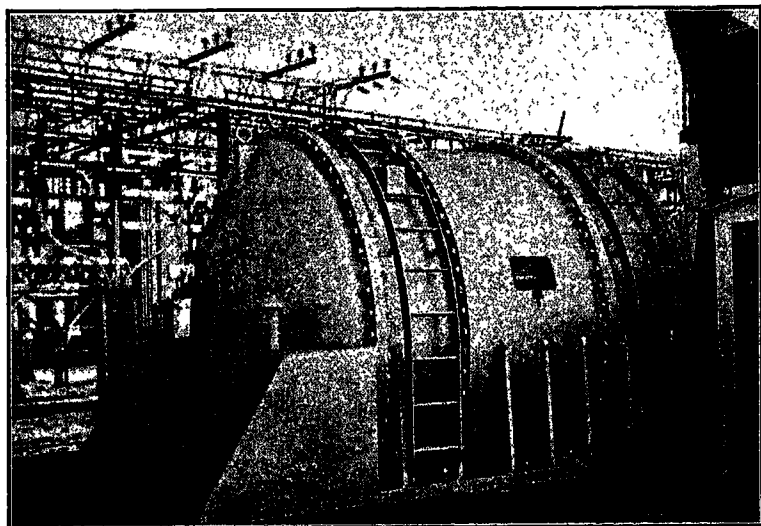


FIG. 22—20,000-KV-A., 900-REV. PER MIN. HYDROGEN-COOLED SYNCHRONOUS CONDENSER
For the Appalachian Electric Power Co.

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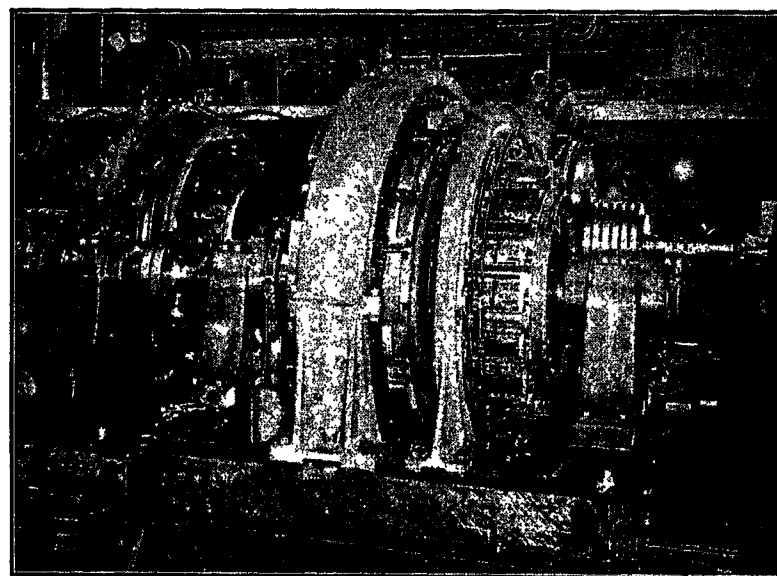


FIG. 23—3000-KW., 60-CYCLE, 360-REV. PER MIN. ROTARY CONVERTER
For the City of Philadelphia

"Changing from Cast Iron and Steel to Fabricated Steel," H. V. Putman and C. C. Brinton, *Elec. Jl.*, July 1928, p. 333.

D-C. MACHINES

The fabrication of parts without the use of castings has been considerably extended during the year, the later developments applying particularly to the rotating

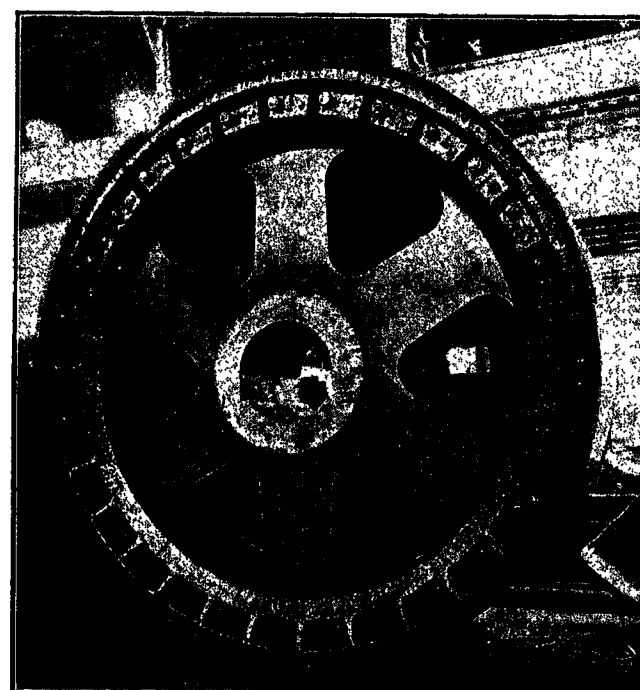


FIG. 24—ARMATURE OF 6000-HP. 70/140-REV. PER MIN. REVERSING MILL MOTOR WITH FABRICATED SPIDER CONSTRUCTION

parts. This method of construction appears to be especially advantageous in the medium and large size units, which, because of their application, are apt to be special and require flexibility in design. The development of the arc welded fabricated construction has given flexibility and still permitted the standard part principle, which separates the machine into parts or

elements, some of which can be used in many different designs and others of which change with each design. Fig. 25 illustrates the fabricated construction of the spider of a G. E. 6000-hp. 70/140 rev. per min. reversing mill motor requiring especially strong spider and supporting structure to withstand the high reversing torques. Fig. 25 illustrates the fabricated construction of a 7000 hp. blooming mill motor built by the Westinghouse Company for the Youngstown Sheet and Tube Company. While the Allis-Chalmers Company has not extended this type of construction to d-c. equipment as extensively as they have in a-c. machines, they anticipate that its use will increase.

Several installations of a new scheme of ventilation have been made. A special volute shaped housing is arranged to make use of the windage of the machine to force the heated air through ducts out of the station and thus maintain a low ambient temperature. Fig. 31 illustrates an installation of this kind at the Wheeling

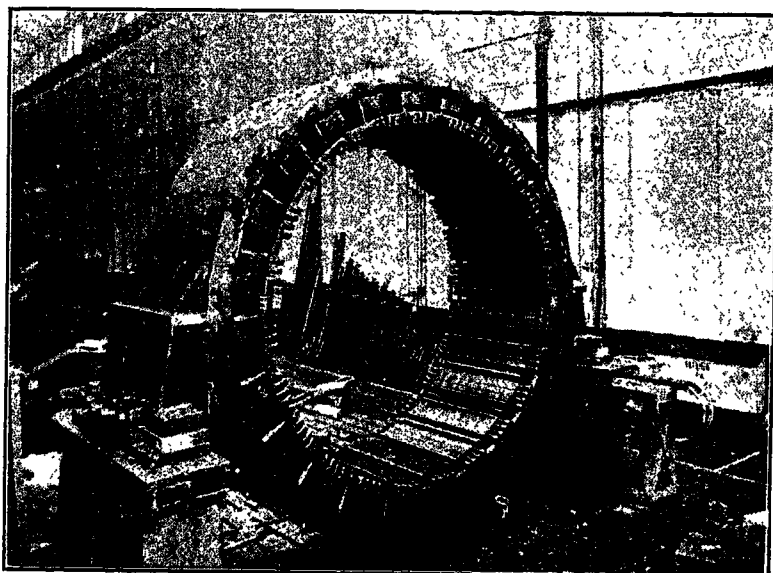


FIG. 25—STATOR OF 7000-HP. BLOOMING MILL MOTOR SHOWING WELDED FABRICATED CONSTRUCTION

Steel Corporation and furnished by the General Electric Company.

MOTOR GENERATOR SETS

Fig. 29 illustrates a 6000-kw. fly wheel induction motor set built by the Allis Chalmers Company to drive a 7000-hp. double unit reversing mill motor of the Illinois Steel Company. The two generators are wound for 700 volts and commutate peak loads of $2\frac{1}{2}$ times nominal rating. The flywheel is of plate construction.

The General Electric Company has furnished some 4000-kw., 5500-kw., and 6000-kw. motor generator sets for electrolytic work with d-c. voltages of 500 and 600. These sets were built with one motor and two generators to take advantage of the higher speeds and efficiencies obtainable by this construction as contrasted with that of a two-unit set.

The Cleveland Terminal electrification has adopted 3000-kw. 3000-volt motor generator sets for power supply. The sets furnished by the General Electric Company consists of two 1500-volt generators con-

nected in series and driven by one synchronous motor, and have a rated overload capacity of 50 per cent for two hours and 200 per cent for 5 minutes.

MOTORS

An interesting motor application is the tandem mill drive of the American Steel and Wire Company furnished by the Westinghouse Company. Five motors

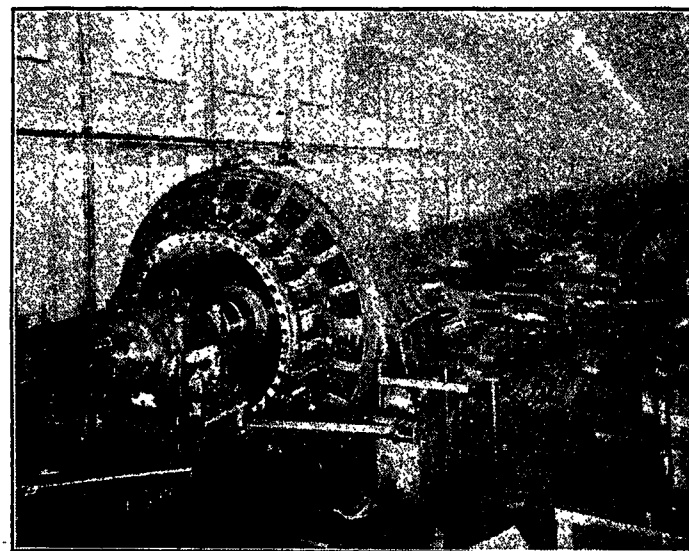


FIG. 26—7000-HP. BLOOMING MILL MOTOR
For the Youngstown Sheet and Tube Company

are mounted on a common bed plate with a distance between centers of 7 ft. This reduction between rolls permits a better steel product, but requires extreme accuracy in the speed regulation, of the motors.

Illustration of wide speed ranges is furnished by the "ultra-speed" planer drive furnished by the Allis Chalmers Company. Minimum cutting speeds of 15

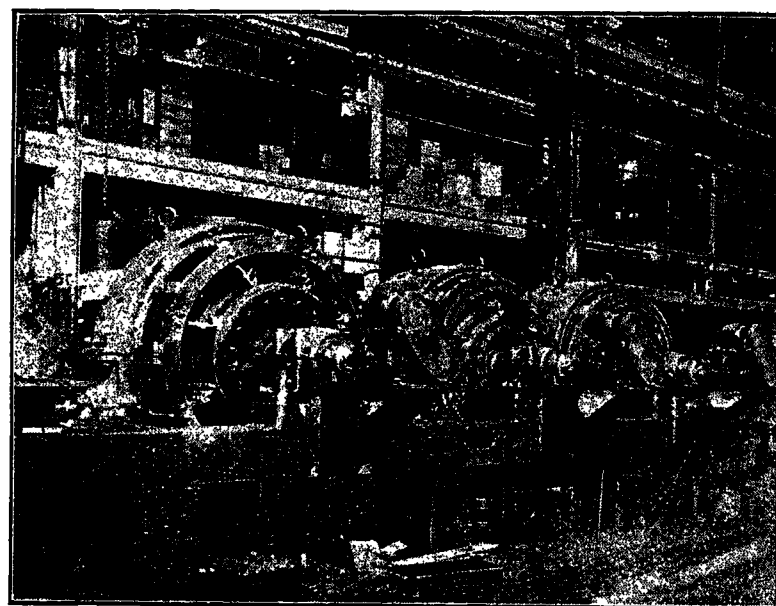


FIG. 27—TANDEM STEEL MILL DRIVE WITH FIVE MOTORS
MOUNTED ON ONE BED PLATE
Built for the American Steel and Wire Company

ft. per minute with return speeds of 180 ft. per minute, or a speed ratio of the motor of 1 to 12 have been obtained.

Gearless traction elevator motors are gaining in use for high-speed equipments. A 140-hp., 85-rev. per min., 250-volt motor built by the General Electric Company is believed to be the largest so far constructed.

It was built of fabricated construction and provided with roller bearings.

The use of d-c. motors and generators for Diesel Electric propulsion of ferries, tugs, tankers, light ships, and freighters has increased. The largest of these is the 4000-hp. drive of the freighter *Courageous* furnished by the General Electric Company. A single 4000-hp. motor is driven by four 800-kw. Diesel engine driven generators.

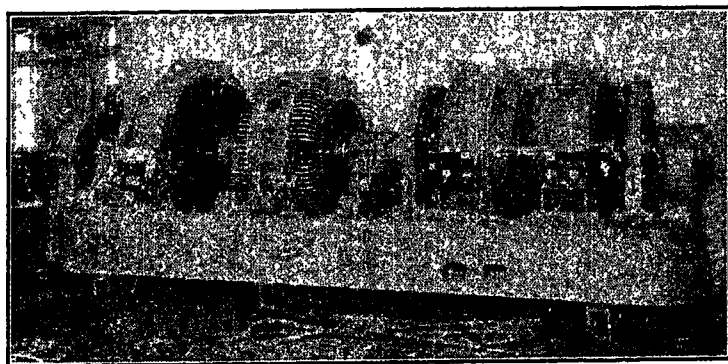


FIG. 28—FIVE-UNIT SHOVEL MOTOR-GENERATOR SET, WITH ONE 860-KW., AND TWO 350-KW. GENERATORS

For the Marion Steam Shovel Company

EXCITERS

Quick change of excitation has been applied in a number of installations to increase system stability during disturbances. Rates of voltage rise of 6400 volts per second with a maximum of 950 volts for a 250-volt exciter have been obtained. As an example of this method, a 165-kw. 250-volt exciter is provided with two field windings, one for a normal excitation of about 4 amperes controlled by a voltage regulator, and the other controlled automatically by a contactor for forcing the excitation up to about 400 amperes. The mag-

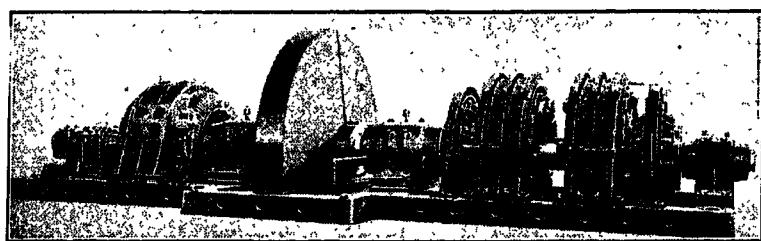


FIG. 29—6000-KW., 700-VOLT D-C. FLYWHEEL MOTOR-GENERATOR SET FOR REVERSING MILL MOTOR SUPPLY

Built for the Illinois Steel Company

net frame is laminated to permit quicker change in field flux. A 40-kw. 275-volt sub exciter provides constant voltage excitation for the main exciter and no rheostat is used in the alternator field.

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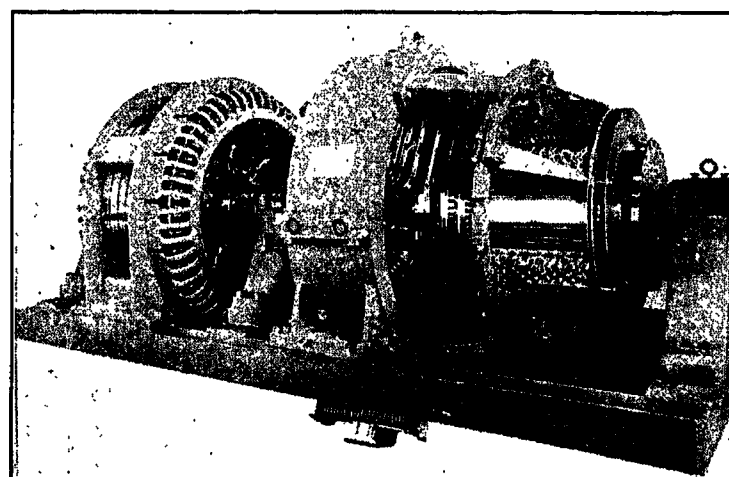


FIG. 30—MOTOR-GENERATOR SET BUILT ENTIRELY OF FABRICATED PARTS

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INDUCTION MOTORS

General. During the past year, there have been interesting developments of new types of small motors,

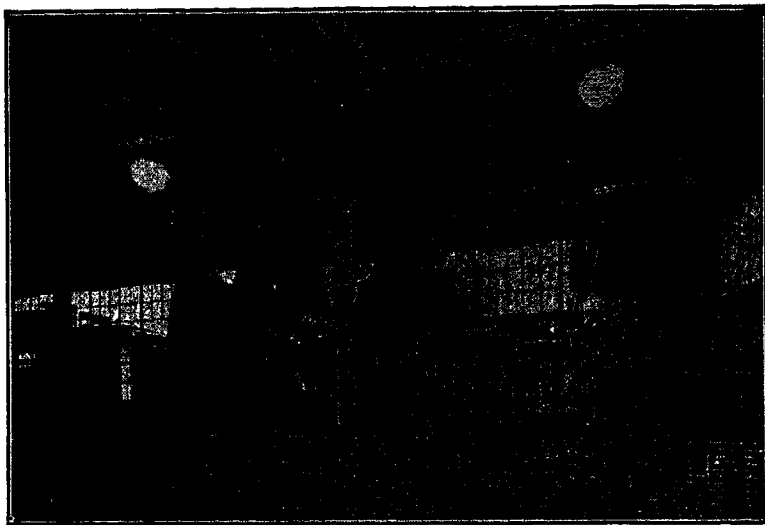


FIG. 31—4000-Kw. MOTOR-GENERATOR SET WITH TWO GENERATORS EQUIPPED WITH VENTILATING HOUSINGS
At the Wheeling Steel Co.

but the larger machines have not been of novel character. The use of single-phase capacitor motors on a considerable scale was inaugurated, and the use of ball bearing, of enclosed fan cooled, and of line start motors was widely extended during 1928.

Capacitor Motors. The need for small single-phase motors of the highest quality for domestic refrigerators,

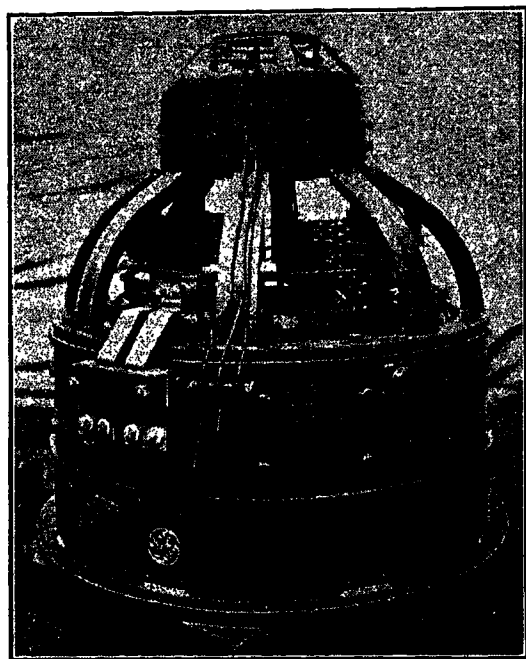


FIG. 32—EXCITERS FOR QUICK RESPONSE EXCITATION SYSTEM

oil burners, and other devices, has spurred manufacturers to a renewed study of the capacitor motor. Reliable low cost capacitors have become available recently, due to the progress of the radio art, and so capacitor motors have now for the first time become economically feasible. Such a motor gives no radio

interferences, has high efficiency and power factor, and gives the minimum of noise. The Howell Electric Company has developed a line of this type of motor; the General Electric Company has put several thousand fractional horsepower capacitor motors into service on domestic refrigerators, and many other manufacturers have entered the field to varying extents. The usual type employed is a normal split-phase motor with a capacitor connected in series with one phase. When more than about 75 per cent starting torque is required, it has been found necessary to use a larger capacitance at start than for running, a switch or auto-transformer with taps being employed to make the changeover. With the present insistent demand of the utility companies for lower starting currents on domestic appliance motors, it is likely that the capacitor motor will grow rapidly in favor.

Repulsion Induction Motors. The use of single-phase repulsion start induction motors in sizes up to 10 hp. has grown steadily during the past year, and a general

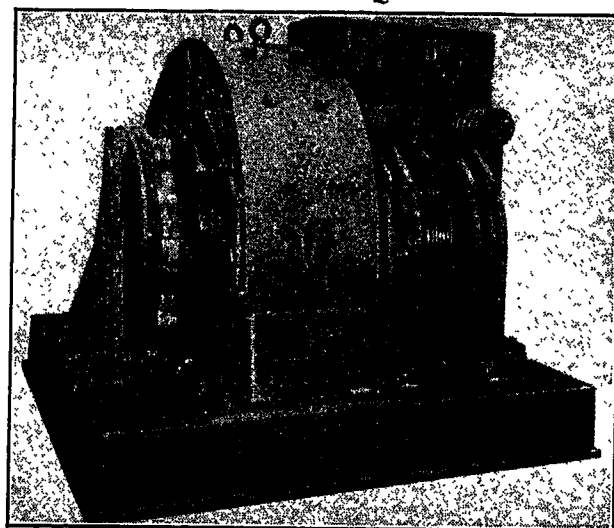


FIG. 33—140-Hp., 85-REV. PER MIN. GEARLESS TRACTION ELEVATOR MOTOR

improvement in characteristics has been obtained. The General Electric Company has recently brought out a novel motor of this type with square punchings, and graded slots, to obtain more efficient utilization of the steel. A photograph of this motor is shown in Fig. 35.

Line Start Motors. Practically all American motor manufacturers are now building extensive lines of motors designed with high impedance, to limit the starting current. This type of motor now represents probably 10 per cent of all the integral horsepower induction motors made in the United States. The designs of motor employed vary considerably, but those with the usual overload capacity of 175 per cent have generally about 500 per cent starting current. The great majority of these motors are built in sizes between $7\frac{1}{2}$ and 30 hp.

Frequency Changers. The use of small induction frequency changers to supply moderately high frequency power to drive high-speed motors has grown steadily. A novel feature now employed with many of these sets

is the provision of taps on the stator winding of the frequency changer motor, so that reduced voltage of normal frequency can be obtained for driving the high-frequency motors when desired. The high frequency motors are wound for a definite voltage, and when they are operated at the lower frequency a proportionately reduced voltage is required. The use of the motor stator as an auto-transformer meets this need.

Two induction synchronous frequency-changers, built for the Niagara, Lockport and Ontario Power Company by Westinghouse, were placed in operation about eight months ago. In addition to carrying heavy overloads, the sets have showed themselves capable of withstanding severe line disturbances without falling out of step. Each synchronous machine is rated 25,000 kv-a. and each induction motor 28,000 hp., making these the largest variable ratio frequency changers in the world.

The General Electric Company is building a similar 25,000 kv-a. set for the Buffalo General Electric Company, the induction motor being rated at 27,500 hp.

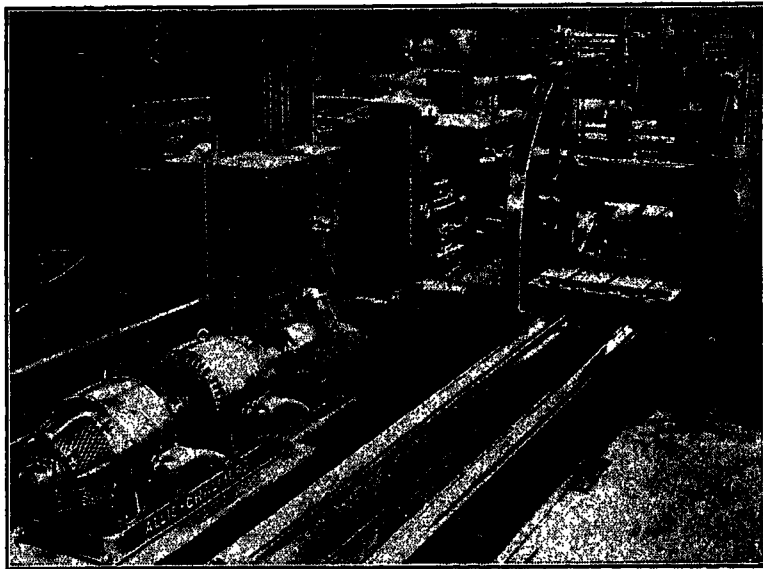


FIG. 34—ULTRA SPEED PLANER DRIVE WITH 12 TO 1 SPEED RATIO

Enclosed Fan Cooled Motors. Enclosed fan cooled motors have grown remarkably in popularity. The initial temperature rise of an open motor is not greatly increased by these modern enclosing features, while, on the other hand, the accumulation of dirt in service on an open motor makes the temperature rise increase very much. The apparent handicap of enclosing is, therefore, converted into a real gain in service temperature rise. A number of methods of enclosing is being used. An interesting type suitable for use in explosive atmosphere has been brought out by the Louis Allis Company. This is made from the standard fan cooled motor, by strengthening the mechanical parts, and other changes.

Large Induction Motors. The use of welded structural steel frames for large induction motors has become well established in the past year. The trials of the U. S. S. *Lexington* and *Saratoga* were successfully completed early in 1928, and the 8 driving motors on each ship were found capable of delivering 27,000 hp. each to the propellers, some 20 per cent in excess of

their rating, without difficulty. The remarkably successful results obtained with electric drive of these ships represent an important achievement of 1928. Several induction motor driven ships are now under construction.

Commutator Motors. An interesting application for the adjustable speed shunt-characteristic commutator motor has been found in the drive of hosiery knitting

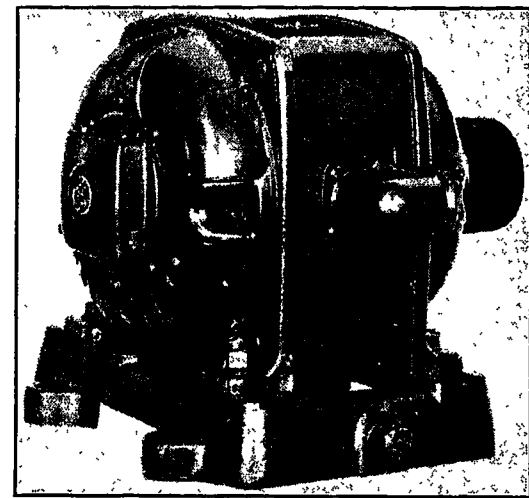


FIG. 35—NOVEL TYPE OF SINGLE-PHASE REPULSION INDUCTION MOTOR

and ring spinning machines. In the latter case, it is desirable to vary the speed of the motor automatically as the bobbin progresses from empty to full, and this is accomplished by automatic means for shifting the brushes of a polyphase adjustable speed shunt commutator motor. The machine as developed is totally enclosed and self-ventilated.

High-Speed Motors. The trend towards the development of large capacity, high-speed motors is shown by

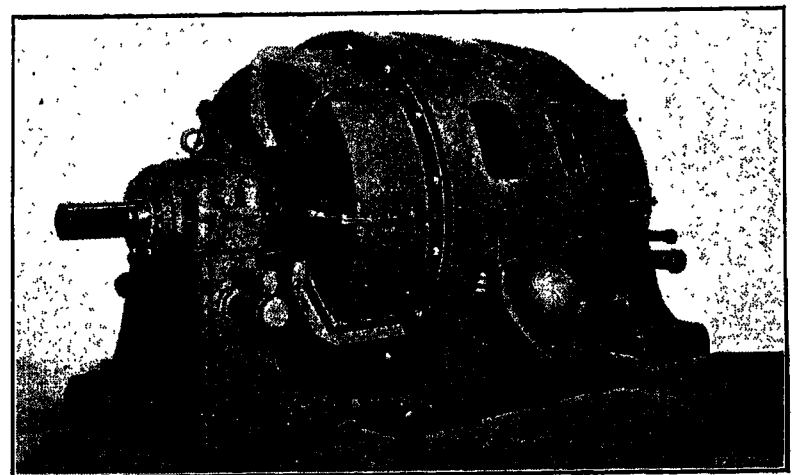


FIG. 36—900-HP., 3600-REV. PER MIN. SQUIRREL-CAGE MOTOR FOR DRIVING BOILER FEED PUMP

some orders recently placed with Westinghouse for eight 1250-hp., 3600-rev. per min. induction motors. They are to be used for driving high-pressure boiler feed pumps.

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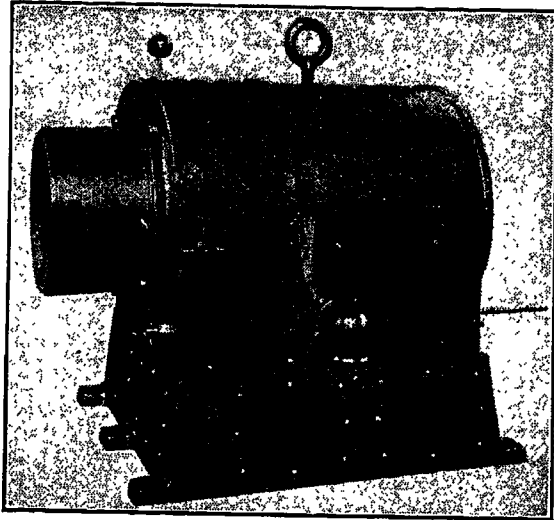


FIG. 37—THREE-PHASE SHUNT COMMUTATOR MOTOR WITH AUTOMATIC SPEED VARIATION FOR SPINNING FRAME DRIVE

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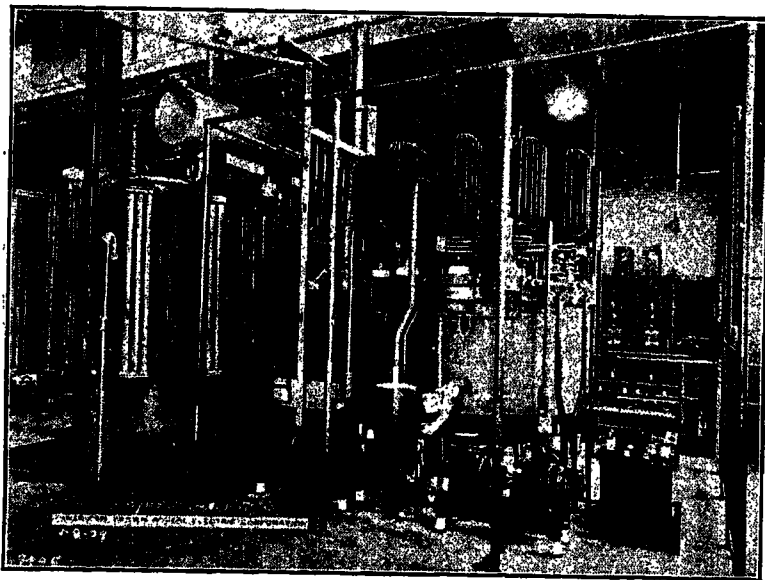


FIG. 38—3000-HP. MERCURY ARC RECTIFIER
For Maypole Substation in Chicago

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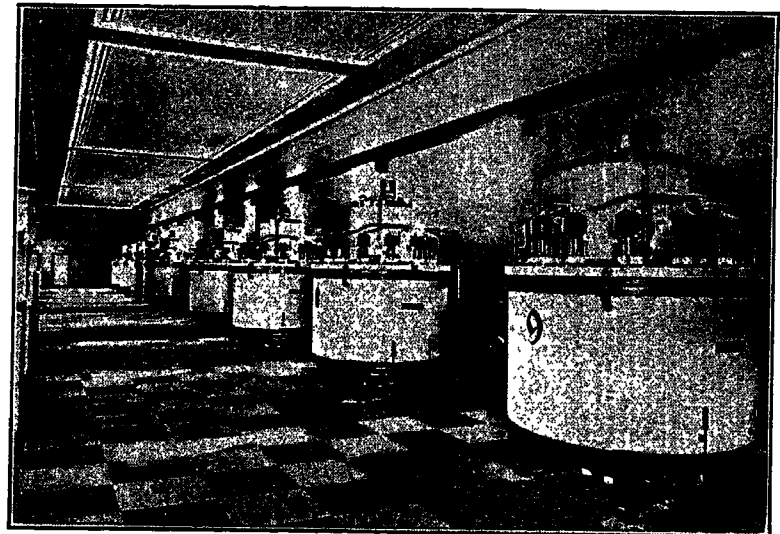


FIG. 39—MERCURY ARC RECTIFIER SUBSTATION
For the Berlin Metropolitan Railway

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MERCURY ARC RECTIFIERS

Mercury arc rectifiers continue to hold the interest in the d-c. railroad and street railway field and rather rapid advances in capacity have been made. Since January 1, 1928 a total of 28 sets have been installed or placed on order in this country, having a total kw. rating of 48,975. The majority of these sets consisted of single tanks and the average rating per tank has materially increased. The same general trend appears to be current in Europe, as over 40 rectifiers with current rating of 4000 to 6000 amperes were installed or placed on order for street railways and electrolytic purposes.

The frequency and deleterious effects of arc backs have been materially decreased. The effect of short circuits has been most evident in the transformers which in some cases have failed due to lack of rigidity of the windings. The seriousness of outages caused by arc backs has been further diminished by improvements in the construction and capacity of pumps, the most important rectifier auxiliary. The installation of arc suppressors has apparently greatly improved service but it does not seem conclusive that the freedom from serious arc backs in some installations should be credited entirely to the arc suppressor.

Larger and better pumping units have been effective in reducing long outages due to the inability to remove the vitiating elements in the vacuum caused by arc backs. Continuity of ignition has been further guaranteed by the provision of anodes in addition to the ones used for arc striking purposes.

Graphitic anodes have given good account of them-

selves during the past twelve months of operation and evidences of their stability were furnished by examinations of some which had been removed from service. Confidence in the metal anode, however, is indicated by their continued use in the largest rectifiers now in service in this country.

Close cooperation has been established between the manufacturers of rectifiers and the manufacturers and operators of communication and central station companies' equipment and system. This has resulted in making available very effective means for the control and suppression of undesirable undulation characteristics in the output from the rectifiers. They have generally taken the form of a low frequency filter including a reactor placed in the d-c. leads from the rectifier. One prominent factor in this cooperative attempt to deal effectively with this interference situation is the realization of the need for a telephone interference factor having a frequency weight characteristic differing from that included in the present unit and based upon the susceptibility of the human ear to tones of different pitch.

The subcommittee has carefully studied the questions of rating, regulation, and efficiency. While these matters together with others, such as nomenclature, have not been finally acted upon, substantial work has been accomplished which will greatly facilitate the reaching of agreements on these essential elements of performance.

The outstanding installations during the past year were two 5000-ampere 625-volt automatic railway outfits installed on the Commonwealth Edison Company's system for railway service. These units were six-phase twelve-anode with arc suppressors but without voltage regulating devices and were supplied by the Brown-Boveri Company. They have an overload

MERCURY ARC RECTIFIERS IN RAILWAY INSTALLATIONS INSTALLED OR ON ORDER SINCE 1927

	No. of sets	Tanks per set	D-c. voltage	Kw. per set	Total kw.	Control
Commonwealth Edison Company, Chicago, Maypole.....	1	1	600	3000	3,000	Auto
Commonwealth Edison Company, Chicago, West Lawn.....	1	1	600	3000	3,000	Auto
Toronto Hydro Electric System, Toronto, Ossington.....	1	1	600	1100	1,100	Auto
Southern Public Utilities Corp., Charlotte, N. C., Eliza. Ave.....	1	1	600	750	750	Manual
City of Calgary, Calgary, Portable.....	1	1	575	600	600	Auto
Union Railway of New York City, New York, St. Peters Ave.....	1	1	625	1000	1,000	Auto
Toronto Hydro Electric System.....	1	1	600	1100	1,100	Auto
American Gas & Electric, New York.....	2	1	600	1000	2,000	Auto
Cons. Mining & Smelting Co. of Canada, Electrolitic.....	3	2	460/560	5600	16,800	Manual
City of Edmonton.....	..	..	575		1,325	Manual
City of Calgary.....	..	..	575		1,200	Auto
City of Halifax.....	1	1	600	1100	1,100	..
Chicago & Joliet.....	1	1	600	500	500	Auto
Columbus Railway Power & Light Co.....	1	2	600	500	1,000	Manual
Columbus Railway Power & Light Co.....	1	1	600	500	500	Auto
Columbus Railway Power & Light Co.....	1	1	600	500	500	Auto
Eastern Mass St. Ry.....	1	2	600	1000	3,000	Manual
Chi. So. Shore & So. Bend Ry.....	1	2	1500		1,500	Auto
Chi. So. Shore & So. Bend Ry.....	1	2	1500		1,500	Auto
Chi. So. Shore & So. Bend Ry.....	1	2	1500		1,500	Auto
Philadelphia Rapid Transit.....	3	1	600	1000	3,000	Auto
Sacramento Northern Railway.....	1	1	1500	500	500	Auto
Piedmont & Northern.....	2	2	1500	750	1,500	Auto
British Columbia Elec. Ry.....	1	1	600	1000	1,000	Manual
					48,975	

capacity of 7500 amperes for two hours or 10,000 amperes for one minute. As these units were not put into service until December, 1928, the brief period of operating service is inadequate as a gage of their all around performance but it is noteworthy that there has been but a negligible number of arc backs and these were inconsequential, as far as could be observed, as the rectifiers were capable of returning to service as quickly as the reclosing breakers could operate. Load swings on one of these units as far as 8000 amperes have been carried without any evidence of limitation.

The Brown Boveri Company developed a new type of rectifier for 3000-kw. which is about 30 per cent smaller than the original units of this capacity. Another type with normal rating as high as 16,000 amperes has been developed, this also showing improved efficiency and reduced weight.

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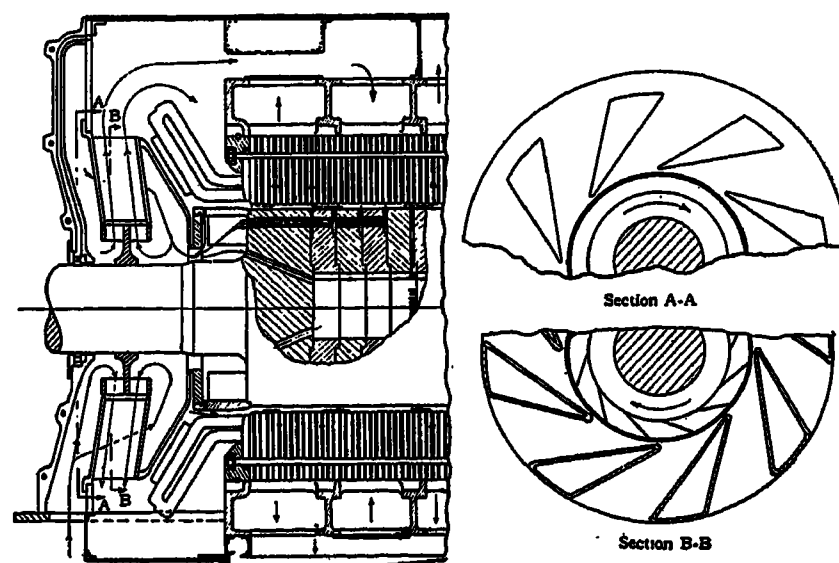
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Discussion

W. J. Foster: These reports are records of notable accomplishments during the past year, and I want to call attention to something that I regard as novel and as adding a great deal in the efficient operation of machinery, especially as I think, to its increase in life, and that is the use of hydrogen ventilation. There is just a slight reference to its use in synchronous condensers, the first commercial application of hydrogen. The 20,000-kv-a. condenser operating in the system of the Appalachian Electric Power Company shown there is not the first one that has been in operation. It is located at Pawtucket, Rhode Island. It was started about the first of August.

It has been gratifying after many years of experimentation and development to have had two machines put into operation. The appeal of hydrogen to engineers is not in its application to synchronous condensers but rather to turbine generators, where the greatest increase in efficiency can be secured, as well as the greatest reduction in the size of machines. That we hope for later. But the operating people have been somewhat reluctant to place orders for such machines. Possibly the next annual report may contain a reference to this application in turbine generators. I certainly hope it will.

C. J. Fechheimer: I think it worth while to call attention to the double-entrance fan, a picture of which is shown in Fig. 19. That photograph does not show the whole as completely as might be, and I want to explain it a little more fully.



[FIG. 1—SCHEMATIC ARRANGEMENT FOR VENTILATING WITH THE NEW DOUBLE ENTRANCE FAN

In the development of these very large units, it is impossible to make the shaft smaller than a certain diameter. As the area between the inner periphery of the fan and the external diameter of the shaft is then too small to admit all the volume of air except at high velocities, with the consequent loss that would accompany

such high velocities, the natural thing one would do is to have a fan with two entrances, one at each side, such as is used frequently for general-purpose fans.

That did not appear as a simple problem at first, but with the scheme as it has been developed it is not only possible to have two entrances, but use is also made of the discharge space beyond the fan so as to increase the fan efficiency. This, in principle, is like that shown in Fig. 1 herewith. About 50 per cent of the air enters the left side of the fan, and the other 50 per cent passes through the axial passages (shown as approximate triangles in the transverse section at the right), at comparatively low velocities. The air then turns through 180 deg. and enters the right side of the fan. After passing through the fan, the two streams unite and

flow through between adjacent outer sides of the axial passages. These passages then function as stationary guides which assist materially toward changing the velocity head of discharge from the fan into static head. (In the longitudinal section this path is shown by dotted lines.)

Thus, the velocity between the fan and the shaft is reduced, and much of the discharged velocity head is converted into static head, both of which increase the efficiency. Efficiencies as high as about 55 per cent have thus been obtained, a considerable improvement over what had been secured before. This development is largely the work of M. D. Ross of the Westinghouse Company. A more complete description by Mr. Ross is given in the *Electric Journal* for March, 1929.

Electric Welding

ANNUAL REPORT OF COMMITTEE ON ELECTRIC WELDING*

To the Board of Directors:

Your Committee on Electric Welding hereby reports the following activities and developments in their field of activity for the fiscal year May 1, 1928-May 1, 1929.

MEETINGS AND PAPERS

Our Committee arranged for the presentation of two papers, at the March 1929 Regional Meeting held at Cincinnati, namely, one by Professor F. P. McKibben, on *Arc Welding in Building and Bridge Construction*; the second paper by Mr. H. V. Putman, on *Design and Construction of Electrical Machinery Using the Arc Welding Process of Fabrication*.

AMERICAN WELDING SOCIETY ACTIVITIES

The American Welding Society through its several Committees, has prepared tentative codes on: (1) Recommended procedure for fusion welding of pressure vessels; (2) Fusion welding and gas cutting in building construction; (3) Nomenclature definitions and symbols, and is developing a code for welding for pressure piping.

The Fundamental Research Committee of the A. W. S. is carrying on a number of researches headed by able representatives of eight of the leading colleges in the country, who are making studies under a number of subjects, some of which are as follows:

1. Resistance welds in low and high carbon steel rods.
2. Study of welds at elevated temperatures.
3. Effect of current density and microstructures on strength of welds.
4. Study of weld joints by X-rays.
5. Study of the fundamentals of the welding arc.
6. Study of welded rail joints.

The American Welding Society is carrying on a great deal of additional detailed work too extensive to mention in this brief report.

COMMERCIAL ACTIVITIES

Bridge Construction. During the year a $\frac{1}{4}$ -mile line of overhead railroad construction at a prominent steel mill was reconstructed by the addition of 75 tons of steel.

The Public Service Co-ordinated Transport Co. of

*COMMITTEE ON ELECTRIC WELDING:

A. M. Candy, Chairman,

C. A. Adams,

P. P. Alexander,

C. W. Bates,

Ernest Bauer,

Alexander Churchward,

O. H. Eschholz,

H. M. Hobart,

C. J. Holslag,

O. L. Ipsen,

J. O. Lincoln,

Ernest Lunn,

A. M. MacOutcheon,

J. W. Owens,

Wm. Spraragen.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

New Jersey successfully repaired by arc welding two pairs of poney trusses each 86 ft. long, forming a combination trolley and highway bridge spanning the tracks of the Central Railroad of New Jersey and the Lehigh Valley Railroad at Middlesex Borough near Bound Brook, N. J. This was a very unique operation, requiring 50 tons of new steel and is described in *Engineering News Record* of October 25, 1928.

At the present time, the Harahan Bridge at Memphis, Tenn., is being reconstructed and widened which work will involve a total of 250 tons of steel. As an indication of the saving possible in this class of work, we cite the following figures, namely, an average of six bids for riveted reconstruction \$15,060 as against an average for the bids by welding construction of \$10,750. This represents a saving of $28\frac{1}{2}$ per cent by welded reconstruction as compared with riveted reconstruction work.

Office Buildings, etc. The Homestead Hotel at Hot Springs, Va. has had a 12-story addition made thereto by the arc welding process, the addition involving 550



FIG. 1—CLEVELAND OFFICE BUILDING. ILLUSTRATES DECREASE IN WEIGHT OF COLUMNS FROM THE FIRST FLOOR TO THE FOURTH FLOOR

tons of steel. The principal consideration in this operation was the elimination of noise, which would have disturbed the guests in the old hotel structure immediately alongside of the new structure. It is difficult to put a direct monetary value upon the elimination of excessive noise for such a proposition.

A combination office and bank building, involving 250 tons of steel, was erected at North Tonawanda, N. Y. for the Tonawanda Power Co.

An office and store building (Upper Carnegie Bldg.) involving 115 tons of steel was completely erected by the arc welding process, using no rivets or bolts, in the City of Cleveland, Ohio, see Figs. 1, 2, 3, and 4.

Factory Type Buildings. Two buildings of this type were constructed in California for the Southern Cali-

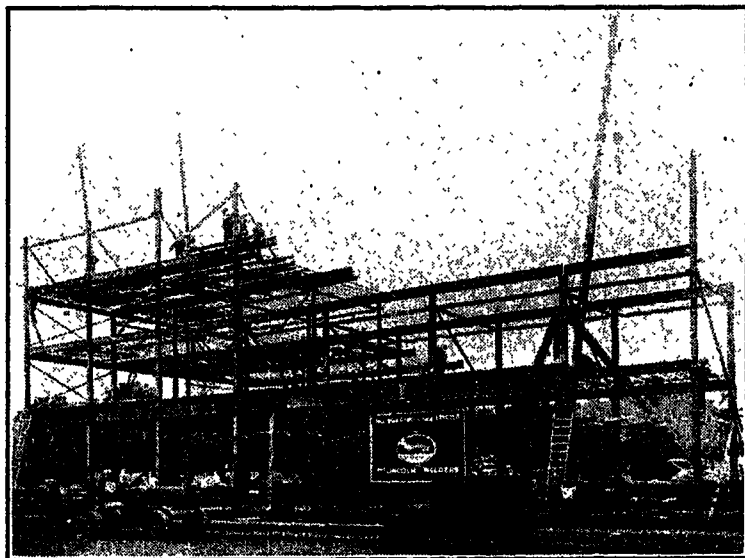


FIG. 2—SHOWS FRAMING PARTLY ERECTED WITH 36-IN. GIRDER WELDED IN POSITION

fornia Edison Co. at Portersville and Visalia, Calif. A building approximately 50 ft. by 100 ft. was constructed by welding at Los Angeles. Several additional small buildings in California were constructed by welding, with trusses from 40 ft. to 75 ft. span. The Ameri-



FIG. 3—DETAIL VIEW ILLUSTRATING WELDED JOINTS IN 36-IN. GIRDERS AND LOCATION OF WELDED OPEN BEAMS FOR SUPPORTING THE FLOOR

can Milling Co. of Omaha, Neb., has built a large hay barn 75 ft by 190 ft., using 100 tons of steel. In central Florida 15 arc-welded buildings have been constructed, principally for citrus packing houses. The largest of these is 117 ft. by 202 ft., containing 200 tons of steel.

One building (Fig. 5) is now nearing completion at North Trafford City, Pa., involving 800 tons of steel and floor space in excess of 100,000 sq. ft. A portion of this operation involves a structure three stories in height, the remaining portion being single story construction.

Thirty-two municipalities in California and eight in Oregon, Louisiana, Mississippi, Arkansas, and Arizona now have sections in their building codes covering the welding of buildings.

According to the new building code sections for these cities, it is now legal for the Commissioner of Buildings in each place to grant, in the same manner as for riveted frames, permits for the erection of electrically welded steel frame buildings.

Pipe Welding. Several installations for welding two lengths of pipe together in the shop to make approximately 40-ft. lengths out of approximately 20-ft. lengths of pipe have been made during the past year. Also some installations for welding longitudinal joints to produce piping in the shop have also been made.

Considerable progress was made during the past year in electric welding gas and oil pipe lines. The method of making the weld, the size of electrode, and welding conditions have been determined for best results and experience has demonstrated the effectiveness of this procedure. Methods of testing the welds have been worked out so that a minimum of interference with the welding procedure is encountered and yet the tests are very effective for determining the quality of the welds.

The welding of pipe lines of municipal water supply

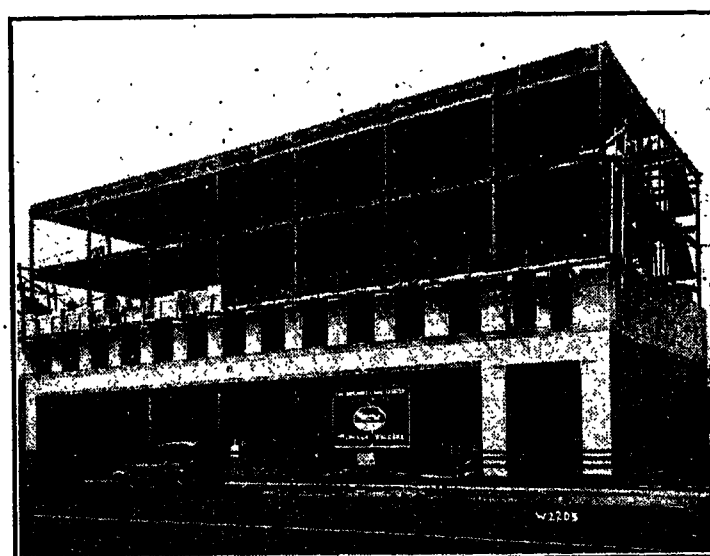


FIG. 4—SHOWS THE BUILDING PARTLY COMPLETED

has progressed rapidly during the past year. Automatic welding machines and procedure control specifications have been developed for this work. Welding technique and testing methods have been determined to insure uniform results on a production basis. The effect of these developments has been to reduce the cost of pipe lines for city water supply systems.

Between 1400 and 1500 miles of pipe line for carrying oil are now being laid in Texas and the South West.

Figs. 6 and 7 illustrate the welding of pipe on one of these lines.

This line is owned by the Texas Pipe Line Co. and has its sea terminus at Port Arthur and runs 714 miles to a place called Monahans, not far from El Paso, Texas.

This pipe carries oil at a pressure of 800 lb. per square inch.

The process of laying the pipe is to get on an average of five 40-ft. lengths lined up on skids along the same axis so that the ends of the pipes being welded are square with each other and weld these five lengths together, turning the pipe every once in a while so that the welder is welding in a substantially downward position. These

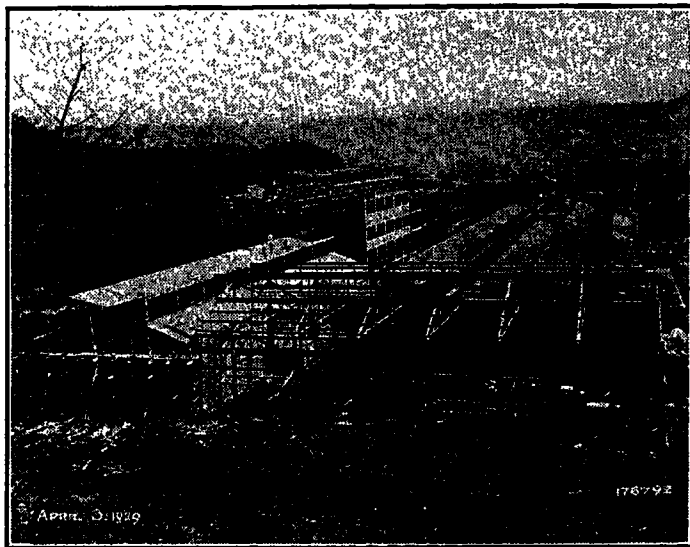


FIG. 5—BUILDING COMPRISES THREE UNITS IN A U GROUP. TRANSVERSE UNIT IN FOREGROUND IS 133 FT. BY 60 FT. LONGITUDINAL BUILDING AT LEFT IS 441 FT. BY 62 FT., 140 FT. OF WHICH IS THREE STORIES IN HEIGHT. LONGITUDINAL BUILDING AT RIGHT IS 460 FT. LONG BY 62 FT. WIDE. A COMBINED OFFICE AND SHIPPING BUILDING AT EXTREME END GIVES A TOTAL FLOOR SPACE IN EXCESS OF 100,000 SQ. FT.

welds are made at the rate of 12 to 14 per day per operator.

Two welds are made on each pipe, a so-called burning in weld and a finishing weld.

One end of each pipe is bell mouthed, and the small end of one pipe is inserted in the large end of the next pipe preparatory to welding.

After the five lengths of pipe are welded into sections the bell mouth end of one section receives the small end of the next section and the two sections are welded together.

This weld is called a "bell-hole weld" and part of this weld must be made overhead. The average rate of making bell hole welds is 8 to 10 per day per operator.

After the pipe is welded, it is lowered into a trench which has been prepared for it and later covered.

The outside of the pipe is protected with a heavy coating of asphaltic material to prevent the earth from coming into contact with the pipe so as to prevent corrosion.

After the pipe is welded it is tested with hydrostatic pressure for tightness, after which the pipe is laid in the trench and covered.

The illustrations show in some detail the process as it is being carried on.

The welding machines are gasoline engines driving



FIG. 6—BELL HOLE WELDING ON 12-IN. PIPE LINE NEAR WELCH, OKLAHOMA. OBSERVE BENDS IN PIPE DUE TO UNEVEN TERRAIN, WHICH CAUSES NO FAILURES

welded sets and these may be transported on wagons or may be dragged from point to point by trucks.

Pressure Vessels. During the past year or so two companies have developed special technique and methods for arc welding of heavy steel plate, oil cracking stills, and other high pressure vessels. One of these companies, for example, has manufactured over a thousand vessels using over 70,000 tons of plates averaging about 3 in. in thickness. Excellent ductility

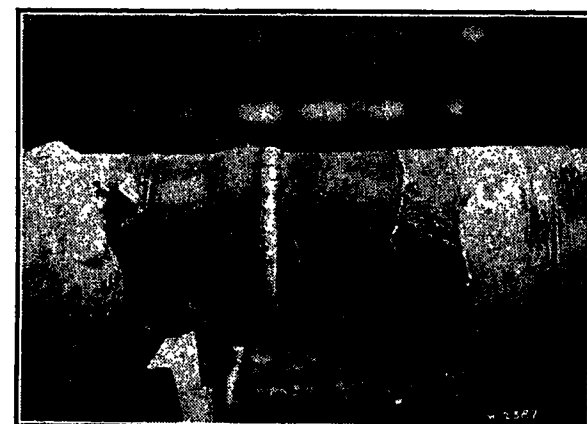


FIG. 7—TYPICAL FINISHED WELDED JOINT IN 12-IN. PIPE LINE

and tensile strength are obtained by the methods used by these two companies which employ covered electrodes with special alloys, heavy currents, and annealing of the structure after welding.

Resistance Welding. The use of spot welders, tubing welders, and flash welders has extended rapidly, es-

pecially in the automotive field, during the past year. Probably the latest large development in the resistance welding field is that of applying flash welders for producing pipe in commercial lengths, up to about 30 in. in

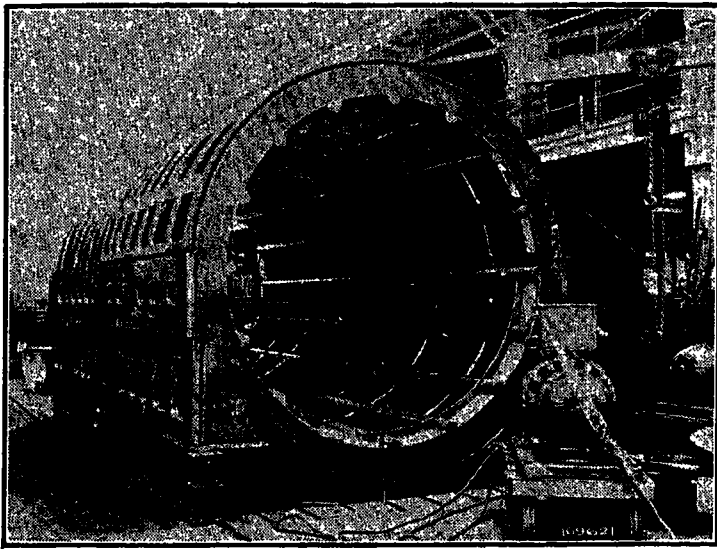


FIG. 8—FRAME FOR 100,000-KV-A., 3600-REV. PER MIN., TURBO GENERATOR WHICH WEIGHS COMPLETE 265,000 POUNDS AND WAS SHIPPED AS A UNIT WITH WINDINGS IN PLACE. IF A CAST FRAME HAD BEEN USED THE WEIGHT WOULD HAVE EXCEEDED THE MAXIMUM CAR CAPACITY FORCING THE COMPLETING OF THE MACHINE ON CUSTOMER'S PROPERTY INSTEAD OF AT THE FACTORY

diameter by $\frac{5}{8}$ in. in thickness, requiring several thousand kv-a. of power to make each longitudinal weld.

Machinery Construction. The use of welded machine structures replacing castings has received great impetus during the past year, especially amongst the manufac-

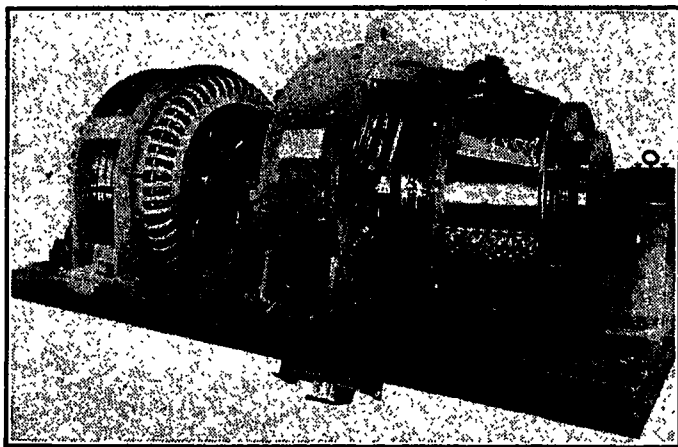


FIG. 9—SHOWS A WELDED MOTOR-GENERATOR SET THE ONLY CASTINGS USED BEING THE PEDESTAL BEARINGS. EVEN THE BRUSH RIGGING FOR THE GENERATOR IS OF WELDED STEEL CONSTRUCTION. THIS SET IS RATED AT 750 KW., 900 REV. PER MIN.

turers of electrical apparatus. The stator for a 160,000-kw. turbo generator has recently been constructed of arc welded steel. (Figs. 8 and 9.) It is undoubtedly safe to say that at the present time such construction by several of the leading manufacturers in the United States has reached the point where not less than 2000 tons per month of such fabricated machines are being produced.

Ship Construction. Metal arc welding is being used extensively in the construction of merchant and naval ships. In both cases, the policy pursued is that of a gradual utilization of the process, rather than an attempt to weld the complete ship. In merchant ship construction the object is reduction in cost, while in naval work, the object is to save weight.

International attention has recently focused on arc welding in naval construction because the weight saved by its use materially assisted the German Navy to mount eleven-inch guns on their new 9000-ton cruisers.

The steam ship Virginia, built during the year by the Newport News Shipbuilding & Drydock Co. for the Panama Pacific Steam Ship Co., embodied sufficient welding in its construction to require the use of 43,000 lb. of electrode welding wire.

Arc welding has also been used extensively in the construction of the 272-ft. yacht *Viking* for Wm. Baker. In this case, it greatly assisted the architects in obtaining the desired graceful lines.

The Fore River Yard of the Bethlehem Shipbuilding Corp. has constructed a number of bulkheads wherein one row of rivets was replaced by a continuous weld.

The Federal Shipbuilding and Drydock Co. of Kearny, N. J., have recently completed two all-welded channel type scows each 116 ft. long, 34 ft. wide, and $10\frac{1}{2}$ ft. deep.

Miscellaneous. The use of automatic welding equipment has increased materially but to date its possibilities have been appreciated by only a very limited section of industry.

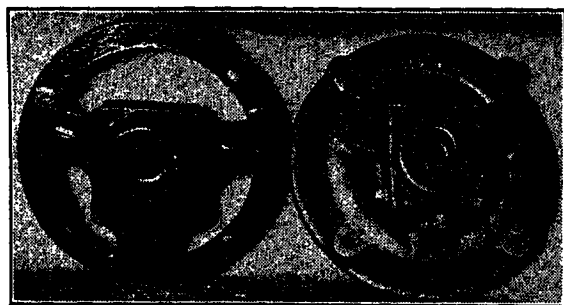
Atomic hydrogen has found many new applications on alloy steels and nonferrous metals. For welding thin sheet steel below No. 16 gage this process has been applied very satisfactorily where smoothness of finish and good ductility are required.

SUMMARY

There are a great many other individual welding applications which might be mentioned but we believe that the above brief résumé summarizes the principal activities in the welding field and will give an insight into welding developments for those who are not directly identified with welding work.

Discussion

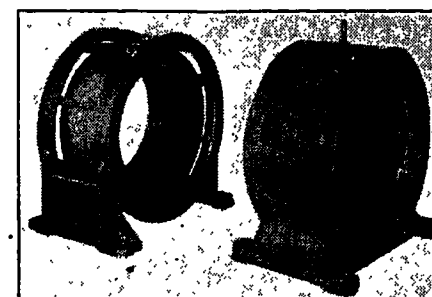
J. C. Lincoln: I want to emphasize the lower cost of electrically welded parts as compared with cast-iron parts. The company with which I am connected makes its products, electrical machinery, largely of steel shapes electrically welded. The accompanying table shows typical reduced costs of a number of parts of equipment. The welded compensator tank shown at J in the illustration costs 80 per cent less than the cast-iron tank. The weight was reduced 60 per cent by use of welded steel.



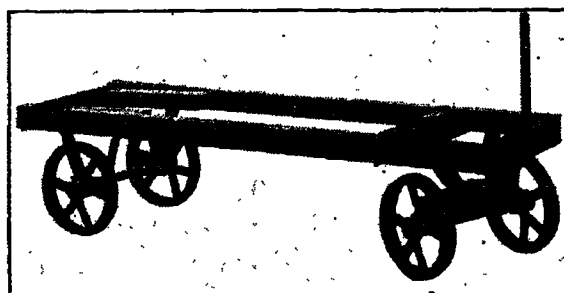
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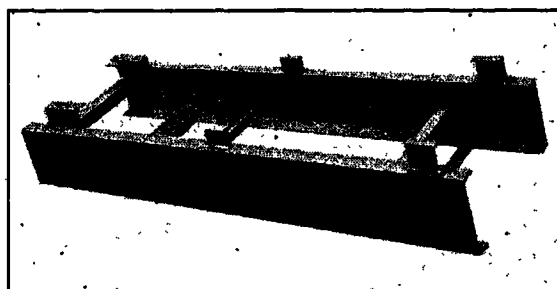
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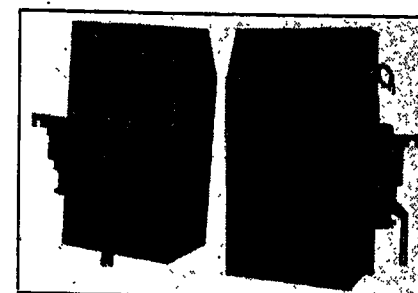
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COMPARISON OF COSTS OF WELDED AND CAST PARTS

Part	Cost					
	Cast iron			Welded Steel		
	Material	Labor	Total	Material	Labor	Total
A. Stator end ring.....	\$1.57	..	\$1.57	\$0.31	\$0.105	\$0.415
B. Frame ring.....	2.89	0.20	3.09	1.13	0.41	1.54
C. Motor stator.....	5.77	0.61	6.38	1.03	0.71	1.74
D. Motor base rails.....	4.99	0.12	5.11	1.54	0.62	2.16
E. Large motor bracket.....	10.88	1.18	12.06	2.98	2.40	5.38
F. Motor spider.....	6.75	2.94	9.69	1.28	4.37	5.65
G. Welder truck.....	..	..	34.00	5.04	2.65	7.70
H. Engine base.....	35.84	1.74	37.58	9.54	3.67	13.21
I. Large motor frame.....	47.13	5.63	52.76	10.65	8.41	19.06
J. Compensator tank.....						

F. C. Caldwell: Consider for a moment the sociological aspects of the development of electric welding. In this method of manufacture we are not only reducing the amount of iron used, to a fraction of that required under the old system, therefore leaving that much more for future generations, but we are also increasing the amount of labor required. One of the social

and economic problems of the present day is, of course, the fact that all along the line the amount of labor needed is being decreased, and some difficulty is being experienced in adapting human conditions to that situation. Here is one case where, while saving material for future generations, we are increasing the amount of labor to something like double that formerly required.

Electrochemistry and Electrometallurgy

ANNUAL REPORT OF COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY*

To the Board of Directors:

The Committee on Electrochemistry and Electrometallurgy submits the following report covering some of the outstanding matters of interest within the field of the committee. Such a review can never claim to be complete. The past year has brought several items of unusual interest. As an innovation in the report of the committee for the present year somewhat more details are given about certain materials and their production, including the features likely to be of interest to electrical engineers. For this reason the number of items covered in the report is somewhat less than in the reports for the several years preceding.

D-C. SUPPLY FOR ELECTROLYTIC USES

Approximately 200,000-kilowatt capacity in direct-current machinery is now purchased yearly by growing electrolytic industries throughout the world. Electrolytic processes are essentially direct-current processes requiring large current at relatively low voltage per unit. The problem of a suitable and economical source of power is therefore of importance, and one requiring careful study to determine the best conditions in any particular case. The generation of direct current may have some advantages as to cost and maintenance, if the electrolytic plant is not far removed from the source of power, and if exhaust or bleed steam can be used to advantage in process work. Such a source of supply, however, is limited in its application and does not permit of interconnection to other sources of power. When power is purchased the problem of converting it from alternating current to direct current usually arises. Synchronous converters and motor-generator sets both find use for this purpose. Possibly large mercury rectifiers may also find extended use in the future. It has been pointed out in several papers which have recently appeared that the proper choice in any particular case must depend (1), upon voltage and other characteristics of the transmission line; (2) the range of voltage, the current, and other characteristics of the electrolytic circuit; (3) The efficiency under particular operating conditions; (4) The initial investment and interest charges. It frequently happens that materials produced by electrochemical means are more costly than

similar materials produced without the expenditure of electrical energy and yet the electrochemical processes are justified by the higher quality of material or by unusual physical or chemical properties. The problem is therefore a complex one which will have much to do with the success or failure of electrolytic production because the power costs are usually a considerable fraction of the total cost per unit of the material.

CHROMIUM PLATING

Chromium plating which was first accomplished 70 years ago has undergone a sensational development in the electroplating field within the past three years. It is only recently that the mechanism of the processes has become sufficiently well understood to make possible its commercial application. From the various uses proposed for chromium plating, it is becoming apparent what may be reasonably expected.

Scratch tests on thin films of chromium indicate that the hardest chromium is harder than any other metals or alloys previously tested. Its ductility is almost zero; its expansivity is about the same as for glass or platinum. It resists tarnish to a remarkable degree. The reflecting power of chromium is 65 per cent as compared with silver 95 per cent. Its electrical conductivity is about that of aluminum.

As a protective coating, thin films are desirable. For some purposes 0.00002 to 0.00004 in. are used over a preliminary coat of copper or nickel. Thicker deposits may tend to crack. Chromium deposits are made from a chromic acid bath to which a sulphate has been added. The anodes are of iron or lead. The conditions for making satisfactory deposits are rather critical as to temperature and current density, the latter ranging from 100 to 300 amperes per square foot. From the standpoint of the electrical engineer, the large amount of energy required is of interest. The voltage across the tank ranges from 6 to 12 volts. The current must be large and since the valence is 6 and the efficiency of the process low, the amount of metal deposited per coulomb is very small. It has been estimated that chromium plating requires 15 times the electrical energy used for nickel plating in equivalent amounts. However, in the case of chromium but little metal is needed. The process brings with it hazards that require carefully designed ventilating systems to protect the workers. In spite of difficulties which may seem numerous, the desirable properties of chromium as a protective coating, its resistance to wear, its hardness, and its pleasing appearance have brought it into use in many industries. Some of the applications which have been made of it have not been successful, as for example, in stamping

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dies. The chromium is brittle and flakes off. In the popular mind chromium is associated with automobile and plumbing fixtures, but in a less conspicuous way chromium plating has proved its worth by prolonging the life of gages, tapes, measuring devices, forming dies, spinning tools, and printing plates.

An important development during 1928, was the installation of several completely automatic equipments for chromium plating. The electroplating industry has learned the value of chemical control and now it is adding automatic electrical control of current density and control of temperature.

ELECTROPLATING OF VARIOUS METALS

In other fields of electroplating, new finishes have been developed. Cadmium plating, which can be easily done on any commercial metal, promises valuable service as a preventative of rust, but it is handicapped by the high price of metal. A process has long been sought for electroplating aluminum on other metals. A step in this direction has been made in the experimental work of depositing aluminum on other metals from organic solutions. New developments are taking place in the electro-deposition of alloys. Whereas this has been largely confined in the past to brass and bronze, there are today a dozen different alloys that may be deposited from aqueous solutions. Nickel-plating continues to increase in spite of the threatened competition of chromium plating. Actually the latter needs an underlying layer of nickel, and so it has been said that chromium plating has actually stimulated the demand for nickel. The trend in nickel plating is towards the use of very pure anodes containing not less than 99 per cent of nickel.

HYDROGEN FOR INDUSTRIAL USES

Industrial uses for hydrogen are rapidly increasing. The electrolytic process is particularly well adapted to the production of hydrogen of a high degree of purity. It is of more than passing interest that a large research laboratory is provided with pure hydrogen piped to the various rooms and consuming more than 2,000,000 cubic feet of hydrogen per month in the experimental work. The demand for pure hydrogen in the fat-hardening industries is increasing and larger electrolytic cell units in some cases amounting to 4 to 5 times the capacity of present installations are being sought. More electrolytic hydrogen is likewise being used in the synthesis of liquid ammonia, the production of which in 1928 was so large that it became the cheapest alkali per unit. It has been found that liquid ammonia is a very convenient form for transporting hydrogen. Of particular interest to electrical engineers is the use of hydrogen as a cooling agent. It naturally diffuses faster than other gases and has a high thermal conductivity so that it can be used to advantage where it is important to remove heat rapidly. High-speed motors and generators are being operated in hydrogen gas in development

tests and a commercial application of hydrogen cooling has recently been made in the case of a large synchronous condenser which is totally enclosed. The capacity of this condenser with hydrogen cooling is said to be 12,500 kv-a., as compared with 10,000 kv-a. if air-cooled. The use of hydrogen for such a purpose is beneficial in other ways, since oxygen and dirt are excluded and the effect of corona on the insulation eliminated. As a safeguard the pressure of hydrogen is maintained above atmospheric pressure and the purity of the gas is continuously recorded. An alarm is sounded if the purity falls below 91 per cent.

COPPER

The change in the copper situation during 1928 was sensational. A sluggish market which had persisted for years with comparatively little prospect of marked advancement was transformed by the increasing demand for this metal. Existing stocks were reduced and outlets for even the high-cost copper provided. Copper as a product of electrochemical industry and as a basic material of electrical construction has a double interest for the electrical engineer. Part of the increased use of copper may be attributed to systematic efforts of a research association to extend its uses and part may be attributed to the growth of electrical industry, which is said to consume in one form or another, more than one-half of the total supply. It has been estimated that the mines of the United States will produce over a million tons during the present year and most of this will be used within this country.

ELECTROLYTIC ZINC

A large plant has recently been installed in Idaho for the production of electrolytic zinc by the "Tainton-Pring" process. Good deposits of very pure zinc are obtained from the strongly acid solutions. The cathodic current density is about 100 amperes per square foot and the voltage per cell about $3\frac{1}{2}$ volts. The nominal capacity of the plant is 50 tons of zinc per day, with provision for trebling this output. Direct current of 16,000 amperes at 500 volts is supplied by two synchronous motor-driven generator units. The electrolytic cells are arranged in two groups of 150 cells, connected in series. Each cell contains 20 aluminum cathodes faced by anodes of a lead alloy. By grounding the mid-point of the circuit, the maximum voltage to ground is reduced to 250 volts. The purified zinc sulphate solution is circulated to the cells until 90 per cent of the zinc has been extracted when the solution contains about 28 per cent acid. The deposition process is a continuous one with periodic changes of the electrolyte. The current efficiency of the electrolytic process averages about 85 per cent. The zinc obtained by this process is of high purity and soft.

NICKEL

Improved smelting and refining methods have re-

sulted in improving the purity of commercial grades of nickel. Electrolytic nickel averaging 99.90 per cent, or better, is the highest grade produced on a commercial scale. This is especially suited to the production of alloys containing high percentages of nickel. It is available as "electro-squares" in a variety of convenient sizes. The ferro-nickel alloys containing large percentages of nickel are finding increased use in radio transformer cores because of their extraordinary permeability.

ALUMINUM

Figures have been published to show that the world's production of aluminum has grown from 24,000 tons in 1908, to 214,000 tons in 1927. Aluminum is typically an electrochemical product. At present two great outlets for aluminum and its alloys are in the manufacture of automobiles and aircraft. It is said that more than 30,000,000 aluminum pistons were made in 1928. Aluminum cylinder heads are beginning to appear. Aluminum alloy frames for motor coaches are decreasing the non-profitable load of these bulky machines. Aluminum crank cases and housings are already familiar. Light and strong alloys are necessary for airplane construction. The strength of a variety of these alloys is now very well known. The fire hazard in the airplane has been reduced and quantity production as in the case of automobiles has become possible. A new material called "alclad" which combines the strength of duralumin and the resistance to corrosion of pure aluminum seems destined to become important in many fields. Aluminum which at one time was considered a material chiefly for cooking utensils, has thus found a wider field. Aluminum cooking utensils continue to increase, but as an outlet for this metal this application is overshadowed by the newer uses in airplanes, automobiles, trucks, railway cars, furniture, roofing, decorative castings, and foil which competes with tin.

ELECTRIC FURNACES

In the electric furnace industry there has been a decided increase in the use of the high-frequency furnace. These furnaces, using a motor-generator type of equipment, have entered the field of silver melting, and it is reported that 3.76 kilograms per kilowatt-hour can be melted with this form of equipment as compared with 2.9 kilograms per kilowatt-hour for the earlier type operated by an oscillator. The high-frequency furnace is well established in the non-ferrous field, and it seems likely that it will find use in the steel foundry as a convenient means of holding the heat. A large number of electric furnaces, mostly of the resistor type, has been installed for the nitriding processes for steel. A very hard surface is obtained similar to that produced by case hardening but superior in some respects.

Ceramic engineers have accomplished much after years of experimentation and many failures, and have

succeeded in introducing the electric furnace into glass and porcelain industries.

In the carbide industries, the desire to increase the unit by increasing the ampere input at 100 to 200 volts has met with difficulties and the electric furnace engineer is confronted with the problem of how to overcome these limits of design without increasing voltage. At 25 to 60 cycles, the present electrical equipment will not permit of commercial operation beyond 3000 amperes per furnace unit.

A number of electrical furnace installations has been recorded in different parts of the world for the production of phosphoric acid and potassium phosphate. There is every indication at the present time that the electric furnace will eventually displace the sulphuric acid process in the manufacture of phosphoric acid. A noteworthy event has been commercialization of the electric furnace for smelting zinc from its ore. At one plant a furnace turning out 50 tons of pure spelter per day has been reported.

The largest peace-time electrolytic alkali-chlorine plant has been put in operation in the vicinity of Charleston, West Virginia. This locality is rapidly becoming a center of electrochemical industry.

BATTERIES

In the battery field the production of batteries for automobiles has continued to increase, the number produced yearly being variously estimated from 11 to 15 millions. The quality of dry cells has increased since the standard specifications were adopted for them several years ago and a proposal to materially increase the minimum requirements for the various sizes and kinds is now before the Sectional Committee on Dry Cells. The dry-cell industry has felt the inroads of the alternating current radio sets, but it is likely that a large number of battery sets will continue to be used. In the field of small rectifiers, the most important development has been the copper-copper oxide type which has displaced many of the electrolytic types.

ELECTROCHEMICAL RESEARCH

Interesting results are being obtained in the study of the nature of conduction found in dielectrics and particularly in insulating oils. This field of research requires a knowledge of both electrical and chemical processes. Relationships have been found between the variation of conductivity with time, the accumulation of space charges, and the final dissymmetry of the potential gradient.

A new material of extreme hardness for machine cutting tools has been placed on the market under the name of "carboly." It consists of tungsten carbide and cobalt. The carbide is extremely hard and the cobalt increases the strength.

The demands of industry for new and pure materials has encouraged the development of electrical processes. Rare metals have been produced by electrolytic methods

and these are gradually coming into the field of technology. We can not anticipate the uses that they may ultimately find in the service of mankind, but the experience with others which we now regard as common indicates that uses rapidly arise when such materials become available commercially. The further purification of the more common metals and the elimination of almost the last fractional percent of the impurities has revealed surprising changes in their mechanical and chemical properties. Electric furnace products bear the brand of superior quality and by the use of electric heating many improvements have been made in working conditions.

The Committee wishes again to acknowledge the helpful cooperation of Professor Colin G. Fink, Secretary of the American Electrochemical Society.

Discussion

E. Fleischmann: May I point out a reference here in the report to the large number of electric furnaces, mostly of the resistor type, which have been installed for the "nitriding" of steel. This, of course, is distinctly a heat-treating process; but it has some phase of metallurgy and chemistry, not electrochemistry, connected with it. It is particularly interesting because it eliminates many of the disadvantages which have been found with the use of electric furnaces for carburizing, and some of the physical disadvantages attendant upon cyaniding. Cyaniding

has caused a good deal of trouble in shops due to poor ventilation and the danger of inhaling the cyanide fumes, and these difficulties are very largely eliminated by nitriding.

Numerous electric and, in fact, other furnaces, have been used for this work; but the electric furnace permits a degree of control which is particularly important in putting a hard case on steel products, which formerly had to be packed in some type of carbonaceous compound; the compound and heavy box heated; and then the whole dumped out and the parts sorted out for further processing. Much of this work is eliminated by the nitriding process; and it seems particularly fitting that a committee of the Institute has taken an interest in it. It is one of the important developments of the uses of electric heating today.

J. C. Lincoln: There is a plating concern in Cleveland called the Metal Protection Company which does nickel plating that is very much superior to anything I have ever seen, and the method is to me at least of very great interest. I have seen pieces of steel $\frac{1}{8}$ in. thick coated with nickel to a thickness of $\frac{1}{16}$ in. on each side, and that strip run through rolls so that the steel is reduced to $\frac{1}{32}$ in. and the nickel to 0.006 or 0.008 inch. That is a very severe mechanical test on the adhesion of the nickel to the steel.

The method used is called the degasification process. The part to be plated is attached to a 12-volt electric circuit and dipped in a tank containing pure sulphuric acid which is connected to the other side of the electric circuit. The current rises to a rather distinct maximum and then very suddenly drops to zero at which time the plate is said to be degasified. After that treatment the nickel is put on in the ordinary way and it is so much more adherent to the steel than it was before, that it will stand this rolling process I speak of without injury to the joint between the nickel and the steel.

Electrophysics

ANNUAL REPORT OF THE ELECTROPHYSICS COMMITTEE*

To the Board of Directors:

One of the Committee's principal functions has been to serve as a connecting organization between the world of physics and the Institute. We have been trying to serve this purpose by encouraging papers which bring in new concepts, phenomena, and terminology from working physicists, and discouraging contributions which are results of "inbreeding." Dielectric phenomena and dielectric theory are two particularly live topics, and there is a constant danger of unnecessarily burdening the Institute publications with contributions which contain more undigested data and unfounded speculations, and which do not bring us any nearer to a rational understanding of the underlying molecular phenomena.

A similar tendency exists in regard to the nature of induced electromotive force, magnetic phenomena, discharges in gases, etc. Men with engineering training or with training in nineteenth-century physics, when they become interested in such physical phenomena, are apt to treat them on a basis which from the point of view of modern physics may be called a blind alley. It has been the committee's concern to see to it that the gap which has grown between electrical engineering and atomic physics within the last fifteen or twenty years, be reduced as much as possible rather than opened wider. Physics is rapidly forging ahead along new paths and it is our privilege and duty as engineers to use as many of its recent achievements and methods as possible, in the solution of our outstanding problems.

DIELECTRICS

A large percentage of papers submitted to the Committee on Electrophysics has to do with dielectrics and their behavior. One of the sessions at the Winter Convention was largely devoted to this topic, and papers were presented on anomalous conduction, dielectric absorption, dielectric constant, power loss, and corona. Several other papers have been since approved for publication or for presentation at future meetings.

Much work on dielectrics is being done under the auspices of the Committee on Electrical Insulation of the National Research Council and also by the

American Society for Testing Materials. Their reports and publications should be consulted in addition to the material found in the A. I. E. E. TRANSACTIONS. There is also a Government Research Committee on this subject in England. Many valuable articles on dielectrics will be found in the *Archiv für Elektrotechnik*, and in some recent British and German books on different phases of dielectric behavior.

Under the auspices of the above mentioned Committee on Electrical Insulation, several subcommittees were formed in 1928, among others a Subcommittee on Physics, V. Karapetoff, Chairman, and Subcommittee on Chemistry, F. M. Clark, Chairman. Both subcommittees are already functioning, and through them many prominent physicists and chemists have been drawn into the study of scientific aspects of dielectrics.

A symposium on dielectrics was participated in by the Subcommittee on Physics, in connection with the April meeting of the American Physical Society in Washington, D. C. This symposium was well attended and will probably lead to greater interest in dielectric behavior among physicists. Several scientific monographs are proposed to be issued, each covering a particular topic, such as breakdown of solids, ionization in gases, dielectric constant, absorption and loss, deterioration by ionic bombardment, etc.

Among topics on dielectrics which are now being considered and studied by various individual physicists in this country, the following may be mentioned:

Mechanism of dielectric breakdown under simple idealized conditions of thin layers, crystals, etc.

Dielectric polarization, absorption, relaxation, loss, and kindred phenomena.

Dielectric constant and its connection with the molecular structure.

Relationship between mechanical and dielectric strength of crystals.

Influence of surface and space charges on conductivity of dielectrics.

Electronic and ionic bombardment of dielectrics, and the resulting physical and chemical changes.

Mobilities of ions.

Nature of ions in various gases.

Distribution of space charge.

Considerable work on dielectrics is being done in connection with an endeavor to improve cable insulation, and it is difficult to determine where the domain of electrophysics ends and that of practical applications begins. In this connection, attention is called to the paper by Professor Dawes presented at the Winter Convention and to the symposium on cables held at the Johns Hopkins University last November. Much

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Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

fruitful work on dielectrics is being done there by Professor John B. Whitehead and his co-workers. Among other investigations, a study has been completed showing that Maxwell's law does not explain the loss in composite dielectrics, and another investigation on losses in air condensers.

While an examination of the year's scientific literature would lead one to expect that investigations of the deterioration of high-voltage cable insulation and related phenomena, had been dropped, the amount of work actually in hand is far greater than in any other period. Several industrial and university laboratories are making intensive investigations of such insulation with special reference to stability of the insulation itself and the factors determining it. Several informal reports have been presented from time to time but none of the work appears to have reached a stage where those responsible for it are ready to present formal published reports. It seems not too much to expect that these investigations will greatly extend our knowledge of the mechanism of insulation failure.

It is of particular interest to note a large number of chemical investigations under way which will contribute to the progress of our knowledge of dielectrics. Of course, most of these researches have been undertaken without any thought of contributing to a study of dielectrics, but the fundamental relationships cleared up will undoubtedly prove useful in applications. Thus, at the last meeting of the American Chemical Society, April 29 to May 3, the following papers of interest to "dielectricians" were presented:

"Sorption of Water Vapor by Cellulose and Its Derivatives," by S. E. Sheppard and P. T. Newsome.

"Influence of Anti-Oxidants on the Oxidation Rate of Linseed Oil," by A. M. Wagner and J. C. Brier.

"Electric Moments and Electric Structure in Aliphatic Compounds," by C. P. Smyth.

"Molecular Structure as Revealed by Dielectric Constant Data," by J. W. Williams.

"The Effect of Symmetry on Molecular Properties," by D. H. Andrews and E. E. Reid.

"Chemical Effect of Electrical Discharge on Gaseous Hydrocarbons," by S. C. Lind and George Glockler.

"Polymerization of Unsaturated Hydrocarbons," by B. T. Brooks.

"Determination of Sulphur in Petroleum Oils," by R. C. Griffin.

HIGH-VOLTAGE RESEARCH

Using the principle of charging capacitors in parallel and discharging them in series, very high impulse voltages have been generated for test purposes. A voltage of 5,000,000 has been produced in this way and even higher voltages have been applied to transmission lines. The phenomena of attenuation, reflection, etc., of traveling waves have been studied by means of the cathode ray oscillograph. This work is being continued on a larger scale. The cathode ray oscillograph was

also used to record impulses on lines due to natural lightning. Only two records were obtained in this first attack on this problem, but a start has been made and more extensive data should be collected this summer. The cathode ray oscillograph was used for a laboratory study of a number of interesting and important phenomena, such as the impulse flashover of insulators and the distribution of transient voltages in transformers. The study of transients on transmission lines by means of the klydonograph has been continued. These instruments are useful in a general study, but the cathode ray oscillograph is now available and is being used for more definite and accurate recording of the shape and amplitude of transients with steep wave fronts. (*Contributed by K. B. McEachron.*)

The year's work at the Ryan Laboratory, Stanford University, California, resulted in three papers. One, by Lissman (A. I. E. E. TRANS., Vol. 48, Jan. 1929, p. 146) analyzes lightning phenomena in the light of laboratory experience, and gives a detailed picture of what actually goes on in a lightning stroke. The second paper, by Carroll and Cozzens (A. I. E. E. TRANS., Vol. 48, Jan. 1929, p. 1) reports results on sphere-gap sparkover voltages up to over one million to ground. It was found that the voltage per inch required to break down gaps in excess of 9 ft. decreased so rapidly with increased spacing as to establish an approximate economic limit of high voltage for power transmission. The final paper, by Dr. J. T. Lusignan (A. I. E. E. TRANS., Vol. 48, Jan. 1929, p. 246), gives the probable history of an a-c. flashover, as obtained from oscillographic and spectroscopic evidence.

DIELECTRIC CONSTANT, MOLECULAR STRUCTURE, AND MOLECULAR MOMENT

During the past year considerable research has been carried out on the subject of molecular moment and its relation to dielectric constant and molecular structure. The work has chiefly centered around the Debye theory. In general, this theory is becoming more and more accepted, although a large number of the researchers find that the theory does not fit in with experimental behavior in a great many instances.

In a study of the variation of the dielectric constant of gases with temperature and pressure, Magdalene Forro finds in the *Z. Physik*, 47, 430 (1928) that the constants of the Debye equation, $(\epsilon - 1)/(\epsilon + 2)(T/d) = \alpha T + b$, change with temperature and pressure. For hydrogen, nitrogen, and air, α (which is the optical contribution to the dielectric constant) is of constant value, while b (which is the permanent dipole contribution) is zero. For carbon monoxide the value of b varies with pressure at constant temperature. The temperature coefficient of b for carbon monoxide indicates a dipole moment of 0.108×10^{-18} at 1 atmosphere to 0.147×10^{-18} at 6 atmospheres of pressure. The variation of the permanent dipole contribution to the dielectric constant can be expressed as either a

linear or as a quadratic function. For carbon dioxide, however, this permanent dipole effect varies with the density as a quadratic function, the dipole moment varying from 0.192×10^{-18} at 1 atmosphere to 0.217×10^{-18} at 6.53 atmospheres..

Study of the molecular moment and dielectric constant in organic and inorganic solutions has been a particularly favored field of investigation during 1928. In general, the work has been in agreement with the results obtained by G. Rock and S. Klosky published in the *Journal of Physical Chemistry*, 33, p. 143 (1929) who have found that the dielectric constant of solvent solutions is essentially that of the dispersion medium. The dielectric constant of solutions may, of course, vary with the concentration. A. Thiel and E. Horn in the *Z. Anorg. Allgem. Chem.* 176, p. 403 (1928) studied the effect of concentration on aqueous solutions of methyl orange, helianthin, and other ampholytes. In the case of methyl orange and the ortho or para amino-benzoic acids the dielectric constant-concentration curves show a continual drop in dielectric constant with increasing concentration. An aqueous solution of helianthin, however, shows a dielectric constant practically the same as water. With some materials these authors report that the dielectric constant drops with increasing concentration to a minimum value beyond which the dielectric constant increases with concentration to a value which is ultimately higher than that of the solvent itself. This agrees with previously published work on urea and other compounds investigated by Harrington (*Physical Review* 8, 581, 1916). The materials which show this increase in dielectric constant with increasing concentration reaching values higher than that of the solvent itself are usually amino derivatives. Future researchers could profitably be concerned with this peculiar characteristic of these compounds. It has, of course, been long recognized that following the dictates of the accepted theory high dielectric constant involves orientation of molecules in the field. N. Marinesco (*Comptes Rendus* 187, 718, 1928) again shows that when a liquid with permanent dipoles is solidified the dielectric constant falls sharply. His explanation is the usually accepted one that after solidification the orientation of dipoles can no longer follow the inversions of the field. The inability of dipoles to orient, however, can be brought about by other means than actual solidification. For instance, a dipole molecule in water solution may be fixed with ion condensation due to its strongly developed electrostatic sheath. Absorption by colloidal hydrophyls may produce the same effect. The water fixed by a colloid can be determined by a study of the dielectric constant change with increasing concentration of the solution.

Debye (*Z. f. Elektrochem.* 34, 450, 1928) has continued his investigation of electric moment. In this publication it is shown that polar molecules have a dipole moment whether or not the dissociation products are charged. The molecular polarization is made up of

two parts, P_1 , the orientation of the molecule as a whole, and P_0 , changes due to the deformation of the electrical equilibrium in the molecule. P_0 and P_1 can be separated for study by observing the molecular polarization at different temperatures, since P_0 is independent of temperature and P_1 varies inversely as the temperature. P_0 and P_1 can also be determined by studies of molecular refraction.

Study of dielectric constant is primarily of physical interest because of its relation to molecular structure. The Debye theory is the tool generally used in this study. Considerable information has been obtained from such researches during the past year. W. O. Ostwald, for instance, in the *Kolloid Z.* 45, 56 (1928) summarizes the situation as follows:

1. Simple hydrocarbons show slight orientation polarization.
2. Halogen derivatives show marked dipole moments, especially the ortho and cis isomers. However, completely chlorinated methane (CCl_4) shows little polarization.
3. The alcohols have an electric moment increasing with the number of CH_2 groups.
4. The aldehydes and ketones are of high electric moment.
5. The ethers, primarily amines and nitrogen bases, possess moderate moment.
6. The nitriles, cyanides, and thiocyanates have high electric moment.
7. The fatty acids have an electric moment greater than 1.
8. The chlor-acetic acids have an electric moment decreasing with the number of chlorine atoms present.
9. The esters show an electric moment between 1.2 and 2.0, increasing in homologous series.
10. The mercaptans have marked electric moment. (Carbon disulphide, however, is of small moment.)
11. High electric moment is shown by the organic nitro compounds.

If the dielectric constant be plotted against the dipole moments a curve is obtained showing a maximum dielectric constant for intermediate values of electric moment. Liquids with a density of 0.8 appear to occupy exceptional positions. In the case of organosols all substances whose additive products do not tend to coagulate have high dipole moments and high dielectric constants. The strongest coagulants have weak or zero dipole moments. Such materials are benzene, carbon tetrachloride, and hexane. The halogen isomers of ethane and benzene have been studied by numerous physicists. A. Errera has continued his investigations started some years ago, on di-chlor substitution products. In previous publications he has already given strong proof of the validity of the Debye theory of permanent dipoles, from work on the di-halogen derivatives of ethane and benzene, by showing that if the charge on the various atoms substituted in a molecule

is known the positions which are occupied on substitution in the parent molecule can be determined.

Van de Walle and Henne have established the position of the atoms in the sereo isomers of chloriodoethylene. From his researches, Errera concludes that the iodine atom in the chloriodoethylene is tervalent and positively charged with respect to chlorine. The nature of the charge is based on the conclusion that if the iodine atom is positive with respect to chlorine then the dipole moment of the cis derivative in which both halogens are nearest must be smaller than the dipole moment of the trans derivative. Errera finds that the dipole moment of the trans isomer is at least twice that of the cis.

An interesting study of molecular structure from the standpoint of dielectric constant and molecular moment has been reported by J. W. Williams and Arnold Weissberger (*J. A. C.* 50, 2332, 1928). These authors have investigated the molecular structure of diphenyl derivatives and from a study of molecular moment at 25 deg. cent. have found that the di-chlor and di-nitro para products have an extended molecular structure. The di-amino (para), however, has a closed up formula. This conclusion agrees with previous researches and is of considerable importance in explaining the properties already recognized for the 4-4' di-amino diphenyl.

Researches for the past five years have indicated that the dielectric constant of liquids varies with pressure to an extent which is more pronounced the higher the dielectric moment of the molecule under investigation. L. Cagniard (*Ann. de Physique* 9, 460, 1928) continues his previous studies and observes that the dielectric constant of carbon tetrachloride, hexane, and cyclohexane, all of which have low molecular moment, is a linear function of the pressure. Study of the variation of the coefficient of $d\epsilon/dp$ with temperature from 20 to 30 deg. shows a change for the dipole gases less than that deduced from the Debye theory. With non-polar gases, however, the change is greater than that deduced from the Debye theory.

According to the Debye theory, the dielectric constant should decrease with increasing field strength. This in many researches has not been observed to the extent indicated by the theory. J. Malsch, however, observes that the effect of voltage is greater with the smaller dielectric constant materials (*Physik. Z.* 29, 770, 1928). The absolute value of the effect of voltage at approximately 250,000 volts per centimeter is indicated as follows:

$$\begin{aligned} d\epsilon/\epsilon &= 1 \text{ per cent for nitrobenzene} \\ &= 0.7 \text{ per cent for water} \\ &= 1.5 \text{ per cent for ethyl alcohol} \end{aligned}$$

F. Kautzsch (*Physik. Z.* 29, 105, 1928) has investigated the dielectric constant of chloroform and ethyl ether under varying field strengths. He has found that the dielectric constant of these materials increases with in-

creasing electric stress but with the higher fields applied the dielectric constant is smaller than that predicted by the Debye theory. Calculations of molecular moment from his researches show that ethyl ether has a value of 1.207×10^{-18} , chloroform 1.026×10^{-18} , and chlorobenzene 0.645×10^{-18} .

P. Boning is publishing a series of articles in the *Zeits. f. Tech. Phys.* 9, 212 (1928) describing the characteristics of dielectrics. In the article referred to he points out that the conduction in solid and liquid insulators appears to be electrolytic in character. There occurs an absorption of ions at the bounding surfaces in heterogeneous materials. Conduction in dielectrics appears to give rise to a system of canals filled with electrolyte. The variation in dielectric constant with voltage, usually observed in technical insulation, is credited by Boning to the absorption of ions at the bounding surfaces of these canals. These articles by Boning are being continued and show considerable merit. (Contributed by F. M. Clark.)

FERROMAGNETISM

Heisenberg has been partially successful in explaining the origin of ferromagnetism on the basis of the spinning electron and the Fermi-Dirac statistical theory. His theoretical deduction is that a material cannot be ferromagnetic unless it is composed of atoms which have 3-quantum electrons and which are symmetrically surrounded by at least eight neighbors.

Honda suggests that the electrons in the nucleus are responsible for the origin of ferromagnetism. His picture avoids the difficulty of the Larmor precession of extra-nuclear electron orbits.

Weiss and Forrer have redetermined the value of the Weiss magneton in iron and nickel, and reviewed the literature to show that the magneton is the unit in all magnetic materials.

The increase in specific heat, due to loss of magnetism near the magnetic transformation temperature, has been measured by Bates for manganese arsenide and compared with the values calculated according to Weiss from the magnetization-temperature curve, with good agreement.

Numerous papers describe experimental and theoretical work on the properties of single crystals of ferromagnetic materials. Honda, Masumoto, and Kaya, and Dussler, report the effect of temperature on the magnetization of single iron crystals. The magnetization curves do not differ radically from those for ordinary iron. In general, single crystals have somewhat higher permeability, and lower coercive force and hysteresis loss, and the properties depend to some extent on crystallographic direction. Kaya has found that the change of electrical resistance with magnetization is different in the various crystallographic directions in a single crystal of nickel. Mahajani in an elaborate calculation has explained the deviation between the direction of the magnetic field and the direction of the

magnetization in single crystals of iron. His calculation is based merely on the magnetic effects of the atom-magnets on each other. Akulov has similarly calculated the magnetostriction of single iron crystals as dependent on crystallographic direction. Peddie has investigated theoretically the effect of temperature.

Elmen has reported the remarkable magnetic properties which he has found in some alloys of iron, cobalt, and nickel. These alloys, named "perminvars," when properly heat treated have permeabilities which are unusually constant up to fields of several gaussses. They have therefore very small hysteresis losses for low flux densities.

Yensen has carefully decarburized and deoxidized iron and observed a maximum permeability of 61,000, considerably higher than any reported by others. An initial permeability of 1150 and hysteresis loss of 300 ergs/cm.³/cycle for $B_{max} = 10,000$ were also reported.

The magnetic characteristics of iron-nickel and other alloys have been investigated anew by Gumlich, Steinhäus, and Kussmann. The magnetic properties of cobalt have also been redetermined by Samuel.

Measurements of the permeability and magnetostriction of various alloys containing iron, cobalt, and nickel have been made by Schulze.

The change in magnetization which occurs discontinuously (Barkhausen Effect) on the steep part of the hysteresis loop, has been found by Bozorth to be the whole change in magnetization, and not a small change superposed on a relatively large continuous change. Measurements of the Barkhausen effect have also been made by Pfaffenberger.

The distribution of heat emission at various points on the hysteresis loop has been determined by Adelsberger and by Constant.

The time lag in magnetization which is frequently ascribed to magnetic viscosity has been shown by Bozorth to be due to the decay of eddy-currents, which takes place at a calculable rate.

Newmann shows experimentally and theoretically how the eddy-current losses in several materials depend on the shape of the hysteresis loop at frequencies up to 2500 cycles per second.

A theory of the aging of Heusler alloys has been proposed by Kussmann and Scharnow, and criticized by Auwers and Weinnoldt. A contribution to the theory of these alloys has also been made by Persson on the basis of his X-ray analysis.

A book entitled "Magnetic Properties of Matter" has recently been published (in English) by Kotaro Honda, of Tohoku Imperial University, Sendai, Japan. (Contributed by O. E. Buckley.)

EXPERIMENTAL INVESTIGATION OF THERMAL RELATIONS OF ENERGY OF MAGNETIZATION

A graduate student at Columbia University, Mr. Walter B. Ellwood, working on hysteresis in iron, has

succeeded in his attempt at a solution of an outstanding problem in magnetism which has hitherto defied attack. The following note, which is a first report on this work, was received from Professor A. P. Wills, under whose direction the investigation was carried on.

Experiments were undertaken for the purpose of determining the mechanism of the degradation of energy which accompanies magnetization in ferromagnetic substances. The experimental method consists in observing the change in temperature of a test specimen produced by a change in the magnetizing force at consecutive intervals in a single cycle of magnetization.

The test specimen is in the form of 106 bars of soft steel drill rod one mm. in diameter. The bars are so mounted as to form 8 coaxial concentric cylinders, and the lengths of the cylinders are so determined as to give the aggregate the form of an ellipsoid of revolution whose minor and major axes are 3.4 cm. and 60 cm. respectively. One hundred and six copper bars of the same dimensions alternate with the steel bars in the structure; 106 thermocouples are constructed by connecting adjacent copper and steel bars alternately with 3 mm. lengths of No. 40 copper wire and No. 34 constantan wire. A coil around the center of the ellipsoid permits the evaluation of the total magnetic flux in the specimen. The entire specimen is embedded in rice powder and placed in an evacuated, silvered glass tube. Adequate thermal insulation isolates the latter from the magnetizing solenoid in which it is placed. The stability of the entire electrical and thermal system is indicated by a zero shift of only 2 mm. per hour on a scale 6 meters from the thermocouple galvanometer. A measure of the uniformity of the magnetizing field in the ellipsoid is obtained by connecting half the thermocouples (associated with the inner bars) in opposition to the other half. Under these circumstances a reversal of the full magnetizing field which produces a rise in temperature of the steel corresponding to a galvanometer deflection of 220 mm., yields a deflection of only 4 mm.

The results of the investigation were represented by curves, the intensity of magnetization and the temperature being plotted against true magnetizing field. One of the curves is the upper part of the usual "hysteresis loop" for the steel. A portion of it indicates the loop obtained when the impressed field is reduced to zero and then restored to its former value. Another curve shows the total change in the temperature of the steel at every stage in the process of demagnetization and reversal of magnetization. A third curve shows the total change in temperature corresponding to the process indicated by the hysteresis curve.

The not inconsiderable cooling of the steel in the neighborhood of zero magnetizing field, as well as the continued cooling accompanying remagnetization on the upper part of the hysteresis loop, are notable features of this record.

PROPAGATION OF ELECTROMAGNETIC WAVES IN SPACE

The subject of wave propagation has been studied theoretically and experimentally and the existence of the Kennelly-Heaviside layer can be regarded as a fact. The resultant signal received at any point is the vector sum of the ground wave and the indirect wave coming down from the ionized layer. The waves radiated from a normal aerial have their electric vectors vertical to the surface of the ground, and almost so at the receiving end. This means in the optical language that the received ground wave is horizontally polarized. The downcoming wave is generally elliptically polarized and the resultant field of both waves is usually complex. This gives rise to bearing errors in direction finding and causes the well known fading.

Hollingworth finds that downcoming waves which are longer than 10,000 meters are usually plane polarized. The direction of the plane is approximately constant during the day but during the sunset and sunrise periods it varies in a manner depending on the distance between the sender and the receiver. At some distances the plane is turned clockwise and at other distances counter-clockwise.

For waves of 400 meters at distances of 100 miles the downcoming components are circularly polarized. This means that both the electric and magnetic vectors have constant amplitude but rotate synchronously, the direction of rotation depending on the direction of the earth's magnetic field. This would mean a right handed rotation in all parts of the Southern hemisphere.

For 15 and 50 meter waves, T. L. Eckersley finds the downcoming waves almost plane polarized, the plane rotating slowly with the period of a few seconds. This should produce fading when a vertical or a horizontal aerial is used for receiving. But fading seems mostly due to a change in intensity of the downcoming waves rather than to a change of phase with respect to the ground wave.

For waves of 400 meters length and the distance of 80 mi., the height of the layer changes during the night from 90 km. at sunset to about 130 km. at one hour before sunrise. But on occasions, during the winter months, heights as high as 250 to 350 km. have been found. (It is understood, of course, that all these heights are only apparent values and higher than actual heights of the ionized layer.)

Measurements using the method of interference fringes show that two sets of fringes may often be obtained, one corresponding to about 100 km. and the other to about 250 km. of height. Hence there must be two regions in the upper atmosphere where the ionization density tends to become a maximum after several hours of darkness. The lower maximum can transmit an incident wave downward to the earth. During the middle of the day a third layer less than 100 km. can exist. It has little reflecting power but it

causes attenuation. This layer is probably the same layer as originally suggested by Lindemann and Dobson.

Examining the theory it seems strange that a radio engineer should be so well acquainted with the physical behavior of the ionized region whereas the pure physicists with the exception of a few workers in the field, are hardly aware of the powerful tool available for studying the conditions in the upper atmosphere by means of radio waves. All the theoretical workers in the field *assume* certain ionic or electronic concentrations in certain portions of this layer in order to confirm certain radio measurements. Would it not be much better if instead of assuming such ionic densities, the pure physicist would take some interest in this phase of work and *predict* from radio measurements what we actually have up there?

Long interval echo signals (duration up to several seconds) have been explained by rays passing through the Heaviside layer into huge empty pockets surrounded by an electron shell and reflected from the shell back to the earth.

So far as thermionic tubes are concerned, the Schottky-Hull (A. W.) screen grid tube has been developed by several manufacturers in this country and abroad with decided success, so that it is possible today to produce stable radio frequency amplification of a very high order and down to very short waves. In Europe also three-grid tubes (Pentodes) have come on the market in order to have tubes of low impedance with still a high amplification factor. (*Contributed by August Hund.*)

PHYSICS OF RADIO COMMUNICATION

In Europe much attention has been given to the effect of trees, buildings, built up areas, etc., on the attenuation of radio waves. Examples of such studies are those of Barfield (*Inst. of Elec. Eng. Jl.*, 1928 and 1929).

Among the important investigations of short wave propagation are those of Heising (*I. R. E.* 16, 75, Jan., 1928), Taylor and Young (*I. R. E.* 16, 561, May, 1928), Mesny (*L'Onde Elec.* 7, 130, April, 1928), Meissner and Rothe (*I. R. E.* 17, 35, Jan., 1929) and others.

Our present knowledge of static is summarized in a paper by Watson Watt (E. W. and W. E. p. 629, Nov., 1928). Carson has shown that it is impossible to eliminate static disturbances in receivers by audio frequency balancing schemes (*I. R. E.* 16, p. 966, 1928).

Advances have been made in the production of oscillations having wavelengths of less than 1 meter. Important publications on this subject are by Yagi (*I. R. E.* p. 715, June, 1928), Hollmann (*I. R. E.* p. 229, Feb., 1929), and Okabe (*Journ. Inst. of E. E. Japan*, March, 1928, p. 284).

An excellent summary of the status of direction finding was recently published in the *I. R. E.* (p. 425 March, 1929) by Smith-Rose.

The Bureau of Standards has developed a successful aircraft radio beacon (*I. R. E.* 16, p. 890. July, 1928). An extensive bibliography on aircraft radio has been published by Jolliffe and Zandoninini (*I. R. E.* 16, p. 985, July, 1928).

In the field of vacuum tubes, Hull has developed a high-voltage two-element gaseous rectifier, and a three-element gas tube, both of remarkable characteristics, (*A. I. E. E. Quarterly TRANS.*, Vol. 47, July 1928, p. 753). Four-element double grid commercial tubes have been developed, and five-element tubes are now in the experimental stage.

The problem of frequency stabilization continues to be a vital problem in radio. Mechanical resonators, such as quartz crystals, regenerative tuning forks, and magnetostriction oscillators operated under carefully controlled conditions, are the best solution yet found to this problem. An extensive bibliography on piezoelectricity has been prepared by Cady (*I. R. E.* 16, April, 1928, p. 521).

The most remarkable discovery that has been made recently in short wave propagation is the discovery by Stormer and Hals of echo signals with time delays as great as 15 seconds after reception of the original signals (*Nature*, Vol. 122, Nov. 3, 1928, p. 681). Similar echoes have also been observed by van der Pol (*Nature*, Vol. 122, Dec. 8, 1928, p. 878.) These Stormer-Hals echoes have aroused great interest, and several explanations have been advanced concerning their origin.

Attention is called to the abstracts appearing each month in the English magazine *Experimental Wireless and Wireless Engineer*. These cover all the important articles on radio communication, and report the most important ones in much more detail than does *Science Abstracts*. (Contributed by F. E. Terman.)

SUBCOMMITTEE ON REACTIVE POWER

In October 1928 the A. I. E. E. published an English edition of the "Questionnaire on the Problem of Reactive Power," prepared by the National Roumanian Institute for the Study of the Development and Utilization of Sources of Energy, for the Advisory Committee for the Improvement of Power Factor of the International Conference on Large High-Voltage Systems.

This is a 21-page 9 by 12-inch pamphlet with an introduction by Dr. C. O. Mailloux. The questionnaire treats in great detail of the theoretical and practical aspects of the subject, with an extensive list of references appended.

The questionnaire has been referred by the Standards Committee of the Institute to the Committee on Electrophysics for an opinion. Since most of the members of this committee are following entirely different lines of work, it was deemed advisable to form a special subcommittee. Dean O. J. Ferguson of the University of Nebraska kindly consented to serve as Chairman of the Subcommittee.

The subject of reactive power has several ramifica-

tions, such as physical and mathematical relations in circuits, the technique of measurement, and elements of cost of power, leading to the subject of rates. The very fact that the Standards Committee referred the foregoing questionnaire to the Committee on Electrophysics indicated that an opinion was desired only on matters of physical facts and their mathematical formulation, and not on the purely engineering and commercial aspects of the situation.

Of course, the subcommittee may find certain physical relationships not only in the circuit aspects and measurements, but in the broad question of power costs as well, and there is no reason why the latter aspect should not be considered in its general terms, without the numerical data. As the work of the subcommittee develops, its chairman will probably find it expedient to cooperate with the Committee on Instruments and Measurements, and possibly with one or two other technical committees.

Statement by O. J. Ferguson, Chairman of the Subcommittee on Reactive Power. The Subcommittee on Reactive Power recognizes the importance of the problem presented by the Roumanian questionnaire. The query is a troublesome one, recurring frequently. It has received the attention of the Institute at various times, as attested by groups of papers and discussions to be found in our publications.

Perhaps the most influential item interfering with arrival at conclusive findings and recommendations is the lack of definite authoritative information as to what are the practical requirements, where we may set limits to a strict adherence to theoretical bases, and where we may recognize empirical approximations.

The answer as to this detail must come from the workers in the various fields. It will differ for commercial power applications from what will be deemed necessary in testing laboratories, or in communication circuits.

Nominally, the task is recognized as an attack upon the following combination of theoretical and practical points:

I. Acceptable definitions for reactive power under each of the following conditions:

1. Single-phase circuits, non-sinusoidal waves.
2. Polyphase circuits.
 - A. Sinusoidal waves, unbalanced circuit.
 - B. Non-sinusoidal waves.
 - a. Balanced circuit.
 - b. Unbalanced circuit.

II. Establishment of practical methods for the measurement of reactive power in each of the above cases.

III. Analysis of present reactive-power clauses in contracts, and establishment of a practical and fair basis for rate-making.

In approaching this problem, we recognize, as stated above, that we can limit ourselves to theoretically correct bases only in so far as these are capable of giving

practicable methods, *i. e.*, comfortable practise, without too great complexity or abstruseness. Rather than wander into involved conditions, we may have to make empirical and arbitrary agreements which will meet the further needs of practise. Rate-research committees, public service commissions, manufacturers, operators, consumers, laboratory investigators, research men,—all of these must be satisfied that our proposals are not inimical to their interests, but are usable with a fair degree of justice, comfort, and simplicity and that the range of usefulness is recognized.

To whatever extent it is possible, new terms and multiplicity of methods must be avoided.

In presenting the above outline, no statement is made as to the province of this committee or that of any other Institute committee. We realize that the study is so far reaching that elements of it will be found to be the peculiar property of certain regular committees. We hope to cooperate with these committees in advancing the solution, without arrogating to ourselves duties which properly are being taken care of elsewhere.

SOME ACTIVE TOPICS IN PHYSICS

One of the purposes of the committee being to act as a connecting link between the Institute and the field of pure physics, the following list of topics will be of interest. It represents some of the subjects on which physicists are working and on which papers are being regularly presented and articles written by the leading investigators. It will be noticed in particular that the old division into mechanics, heat, light, electricity, and sound, has been more or less obliterated, the electron theory and the quantum mechanics being the dominant foundation of most of the researches, except in acoustics.

Scattering of electrons by gases, liquids, and solids.

Diffraction of electrons by thin films and by crystals.

Absorption of electrons by vapors.

Effect of electrostatic and magnetic fields upon electrons, ions, and neutral molecules.

Spectra of various substances under different conditions, as bearing upon the nature of their atomic and molecular structure.

Energy distribution, attenuation, and absorption of radiation at different wavelengths.

Photoelectricity and photoelectric cells.

Effect of electric and magnetic fields upon spectra, and correlation of these effects with the atomic and molecular structure.

X-rays; their wavelength, electron levels, diffraction, fine structure, polarization, ejection of photoelectrons.

Characteristics of sparks and other discharges, including their spectra.

Thermionic emission and properties of triode valves.

Compton effect, Raman effect.

Behavior of electrons like waves and behavior of light quanta like particles; bridging the gap between matter, electricity, and energy.

Nature of light waves and of electrons.

Conduction in metals from the point of view of the new quantum mechanics.

Nature of magnetism.

Magnetic properties of crystals.

Experimental and theoretical study of atmospheric electricity and terrestrial magnetism, in terms of moving ions and of radiations.

Structure of the universe in terms of astronomical and spectroscopic evidence, assisted by Einstein's generalized theory of relativity.

New statistical mechanics, wave mechanics, quantum relations, indetermination principle, etc.

Quantum mechanics of chemical reactions.

Atomic structure and chemical valency.

NOTE. Attention is also called to Dr. M. I. Pupin's Editorial on *1928 Progress in Physics*, in the A. I. E. E. JOURNAL for February 1929, Vol. 48, p. 92.

DIFFERENTIATION OF ACTIVITIES AMONG PHYSICISTS

Within the last twenty years, the Institute has seen several groups of specialists among electrical engineers form societies of their own, apparently feeling that the parent body was not able to devote to their particular activities as much time and space as was needed. As such special societies may be named those devoted to welding, electrochemistry, iron and steel industry, illumination, and radio.

It seems as if a similar differentiation is taking place in physics. The Optical Society of America was formed some years ago as an offshoot of the American Physical Society, and now the Acoustical Society of America is in the process of formation. In Germany they already have a separate prosperous Society for Applied Physics, with its own periodical. Considering the large number of physicists employed in the American industries, a formation of some such society is quite possible in this country unless the parent body anticipates such a move by a proper subdivision of its body into several "subject sections" and committees.

A GENERAL TREND IN PHYSICAL CONCEPTS

The present day period in physics may be said to have begun with the discovery of the electron in the closing years of the nineteenth century. This meant a new atomic concept of electricity. The introduction of the idea of quantum of energy, as the smallest amount of energy in a "chunk" of radiation of a given frequency, meant another new concept, namely, the atomicity of energy, at least in one of its forms. Einstein's relativity followed in 1905, and has brought in another new idea, namely that a physical "law" may be different depending upon the size of the continuum to which it is applied and the magnitude of the velocities which come into play. In the Bohr-Sommerfeld theory of the atom (1913-1915), the three new concepts, namely those of electron, quantum, and relativity, were brought together in a masterly way, to explain the observed complex structure of various spectra. Later, similar ideas were extended to molecular spectra and

to the theory of specific heats, as being due to different forms of motion of the parts of a molecule relatively to one another.

Thus, an era of "picture theories" of the atomic structure was ushered in. Electrons were endowed with various forms of motion about a central nucleus, to explain this or that phenomenon; atoms were endowed with suitable forms of motion within a molecule, to explain some other phenomena, and when a particular feature of a spectrum could not be accounted for, new motions were invented to explain it (for example, the spinning electron). In other cases, the observed spectra did not show all the lines predicted by the theory, and certain "principles" or "postulates" were introduced to exclude such lines *a priori* as not being in accord with one of these principles.

However, the picture-theory period was only short-lived, partly because the pictures themselves became unduly complex, especially for heavier atoms, partly because the theory proved to be inadequate on some essential points, and partly because in the very nature of the phenomena statistical results were desired, rather than an actual orbit of this or that electron in a particular atom. But a statistical problem, where billions of atoms are to be considered simultaneously, and where only the probability of a certain event is sought, rather than its certainty for a given atom, hardly lends itself to a picture. Just as an extreme advocacy of graphical methods in a branch of engineering usually leads to a reaction in favor of an analytical method, so the picture-theory period yielded its place almost overnight to a "mathematical-function" period in the midst of which we are now laboring.

Several brilliant European mathematical physicists, such as Heisenberg, Born, Jordan, Pauli, de Broglie, Dirac, Fermi, and Schrödinger, have developed various aspects of this new point of view, and while it would be entirely out of place to go into the details here, the following few remarks may indicate the general trend.¹ Ideas are more general than objects or phenomena, and we are apt to come nearer the true interpretation of the universe by adhering as closely as possible to general ideas rather than by evolving specific pictures, especially if the latter have been borrowed from the big world of every day experience and transferred without change into the unknown intra-atomic world. But quantitative ideas are best expressed by mathematical formulas and operations, and so the problem is reduced to devising such formulas and operations and using them to describe and to predict phenomena, even though we may not be able to construct corresponding pictures within the atom. There is no contradiction in this

because an individual atom is not yet susceptible to direct observation. The principal point to achieve is to make the mathematical theory agree with the observed phenomena in the minutest amounts of matter and energy with which an experimentalist deals.

To put this in a different form: Suppose we write two equations, such as $ax + by = c$ and $mx + ny = p$. One could write a story about a merchant who bought x yards of cloth, etc., and make this story fit the equations. One could also write an entirely different story, say about two trains which start from two stations distant x miles from each other, etc., and again fit the equations. The number of such stories is infinite, whereas the two equations are the same, and presumably they stand for a much more general truth and relationship in the human mind than any of the stories.

It is not for the present writer to criticize either the picture or the formula tendency. Both are temporary, and a new genius may in a few years give us a new idea which will combine a keen mathematical analysis with a definite physical picture. We need a picture not only because our human nature demands it, but also because with the improvement in experimental methods smaller and smaller amounts of space, matter, and energy will be susceptible to direct observation, and will cease to be mere statistical elements. In the meanwhile, the statistical method of quantum mechanics reigns supreme, new achievements for it are recorded at every meeting of physicists and in every issue of physical periodicals. One who fails to learn the new mathematical methods will soon be unable to follow the progress even of experimental physics, because a large portion of experiments are nowadays performed either to test the new theories, or to furnish the needed numerical data for them.

As Haas correctly points out,² should the new point of view persist for any length of time, it cannot fail to affect our whole attitude towards physical laws and interpretation of nature. According to it, matter and radiant energy are both atomic, and do not differ radically from each other. Under certain circumstances, electrons behave like waves and waves behave like chunks of matter. Energy is converted into matter, and vice versa, and this process is going on in the universe continually, creating new worlds and destroying the old. A physical law does not dominate an event but merely establishes probabilities for this or that percentage, just as a statistical law does not affect births or deaths in a species of living beings. In the big visual world we may speak of an instantaneous position of a material point and at the same time of its instantaneous velocity. In the sub-atomic world, according to Heisenberg's principle of indeterminateness, such a

1. A symposium on Quantum Mechanics was held under the joint auspices of the American Physical Society and American Mathematical Society in New York City on December 31, 1928. Most of the papers and discussions may be found in the April 1929 issue of the *Franklin Institute Journal*.

2. Arthur Haas, "Materiewellen und Quantenmechanik," *Akademische Verlags-gesellschaft*, 1929, Chapter 19. See also V. Karapetoff, "Picture Theories Inadequate," an article to be published in the *Electrical World* during 1929.

statement would be absurd. If the coordinates of an electron are given we can only ask about the probability of a certain velocity, and vice versa. In the big world of interstellar spaces other laws reign supreme, Euclidian geometry and ordinary mechanics hold no more, and what we observe in our every day life (or even in our best equipped laboratories) is but a very narrow aspect of the real laws of nature. We do not see the bigger relativity aspects of the fundamental laws of nature,

because our distances are too small and our velocities too low. We do not see the fine-structure aspects of the same laws because of the crudity of our apparatus which permits our observing the microcosm only statistically.

The new attitude is one of humility, and if it is an attempt to free the laws of nature from an anthropocentric point of view, future generations will welcome it as a step in the right direction.

VLADIMIR KARAPETOFF, *Chairman.*

General Power Applications

ANNUAL REPORT OF COMMITTEE ON GENERAL POWER APPLICATIONS*

To the Board of Directors:

Your Committee on General Power Applications has attempted to keep in close touch with the development of power applications during the year through the selection by the various members of the committee of specific industries in which they were deeply interested and on which they agreed to furnish a condensed report early in 1929.

It was hoped by this method that suggestions for papers and needs for new applications would be brought out and that interesting material would be obtained covering the development of power applications in outstanding industries.

Your committee believes that constructive results can be obtained by the continued application of this idea so that the annual report of the committee will not only represent a first hand account of the year's developments in numerous fields but will also develop the desirability for written discussion of outstanding features and bring to light the need for specific applications of power to processes which have not been modernized.

No attempt has been made to cover the entire industrial field so that there are undoubtedly many new applications which have not been brought to the attention of your committee. An effort was made, however, to cover the outstanding developments in basic industries which should be a true measure of the advance during the past year.

MARINE EQUIPMENT

During the year 1928 there were placed in commission, or under construction, a total of 38 electrically propelled vessels of various sizes and types ranging from the small river towboat to the most modern of passenger liners. The aggregate shaft horsepower of the electrical equipment in these vessels was over 132,400, of which 88 per cent was supplied by turbines and 12 per cent by Diesel engines. However, of the 38 vessels electrified, 24 were of the Diesel electric drive.

Outstanding developments in the application of electricity to marine work during 1928 were the launching of the largest electrically propelled passenger liner, the breaking of all existing speed records for capital

naval ships by the airplane carriers, *Saratoga* and *Lexington*, and the installation on three freighters of the biggest d-c. motors ever put on a ship.

Turbine Electric. The passenger liner *Virginia* is the second of the three electrically propelled passenger liners being built for the Panama-Pacific Line of the International Mercantile Marine Company. This vessel, somewhat larger than the *California* launched in 1927, has a displacement exceeding 30,000 tons at load draft and develops 16½ to 18 knots with a maximum power development of 17,000 shaft hp. The propeller shafts are each driven by a 8500-hp. reversible type motor.

The U. S. Navy airplane carriers *Saratoga* and *Lexington* underwent their speed trials and were put into active service during the past year. The U. S. S. *Saratoga*, with electric propelling equipment of 180,000 shaft-hp., maintained a speed of 33.42 knots over a measured mile. The *Lexington* on its acceptance trial last November developed 210,000 shaft-hp. and a speed of 34.62 knots. These tests broke all speed records for capital naval ships.

Five new Coast Guard cutters have turbine electric drive of unusual type. Each boat has a single turbo-generator set which supplies power to a single synchronous motor on the main drive. In addition, each boat has two dual drive sets, (steam turbine, alternator, and d-c. generator all coupled) which produce direct current for excitation and some auxiliaries. At normal ship speeds (40 to 60 cycles), the alternator, operating as a synchronous motor, drives the d-c. generator by power from the main generating set. When maneuvering, the frequency drops below 40 cycles, the turbine of the dual drive set then drives both electrical machines producing both direct and alternating current. The result is that as much auxiliary power as possible is supplied from the main generating set giving a high over-all efficiency in operation.

Diesel Electric. Outstanding in this field was the replacement in three 10,000-ton freighters, owned by the U. S. Shipping Board, of geared turbine drive by Diesel electric equipment. The motors, shown in Fig. 1, are rated at 4500 hp. and developed on trial momentarily 8000 hp. without distress. The slow speed propeller adopted for this drive increased the speed of these vessels from 10½ to more than 13 knots. This drive required less space and was lighter than the original equipment, besides increasing the efficiency of operation.

Four Diesel engine-driven d-c. generators, each rated 800 kw., 250 rev. per min., 385 volts, supply the single propelling motor which is direct connected to the shaft. Control is of variable voltage type, maximum power being obtained by connecting the armature of the four

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main generators and the main motor in series. For reduced speed, one or more of the generators may be cut out of line.

The highest powered Diesel electric drive tugs in the world, the *Trinidad* and the *Chagres*, were placed in service by the Panama Canal Commission. These tugs have a cruising range of 7000 mi. and are equipped with complete fire fighting units. Due to the diversified demand on the services of these vessels, they are completely equipped with auxiliaries, all of which are electrically driven.

Three lightships, operated by the Bureau of Lighthouse Service, were provided with Diesel electric drive during the year. Economy of fuel and availability of power were the deciding features in these installations.

There was also evidenced during the year an increased tendency to equip various river crafts with Diesel electric drive. This tendency is especially marked

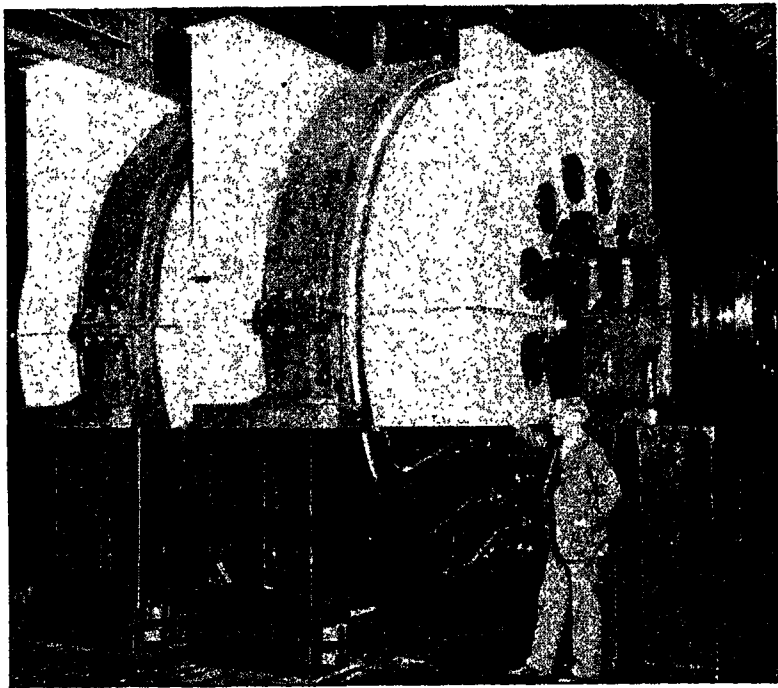


FIG. 1—4500-HP., D-C. MOTOR FOR PROPELLING A 10,000-TON FREIGHTER

where the river to be navigated is swift, shallow, and tortuous, requiring perfect control while maneuvering.

Two new fleet submarines, the V5 and V6, the largest in the Navy, were commissioned during the year. These vessels are designed for extensive cruising and, therefore, involve many improvements over the old type of submersible craft. Particularly noteworthy are the controls, all manually operated, which permit 15 different combinations of diving and charging. Another point is the perfection of motor bearings, which permit diving at an angle of 30 deg.

It is of interest to note that foreign countries are awakening to the possibility of electric drive on ships. The *Viceroy of India*, a 19,000-ton turbine electric passenger liner, is the first large ship of its kind built in England. Two Diesel electric tugs are under construction in Italy, the first of this type to be built in that country. Germany has several cargo vessels

under construction that will employ Diesel electric drive, full details of which have not been published.

ELECTRIC RAILWAYS

Although electric railways come under the jurisdiction of the Transportation Committee, there are several unusual applications of power in this field which it will be well to mention briefly.

To speed up the classification of freight and to eliminate as far as possible the hazardous occupation of car riding, several railroads have adopted electric retarders

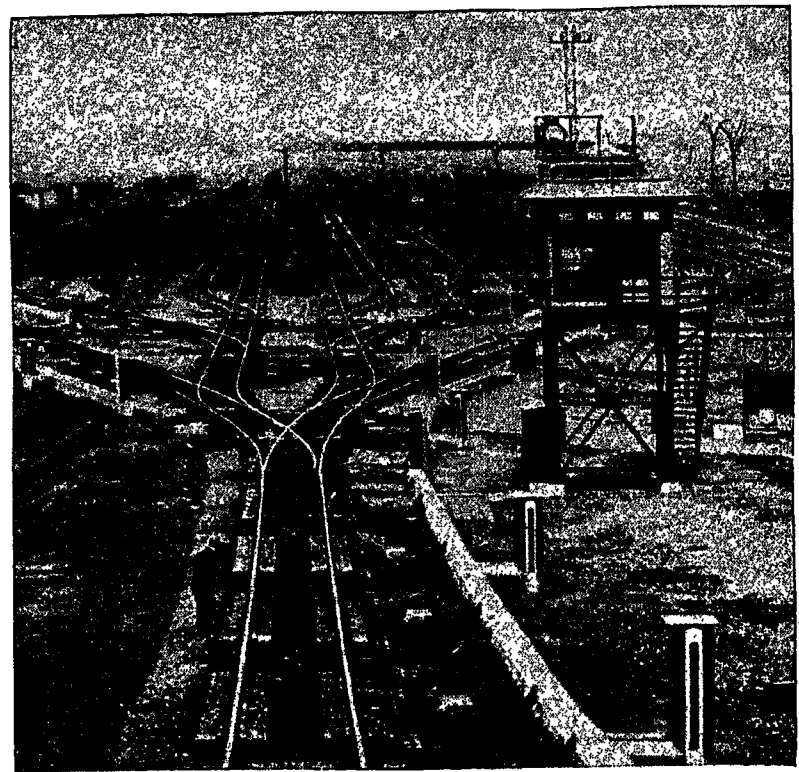


FIG. 2—ELECTRIC CAR RETARDERS IN THE SELKIRK YARD OF THE NEW YORK CENTRAL

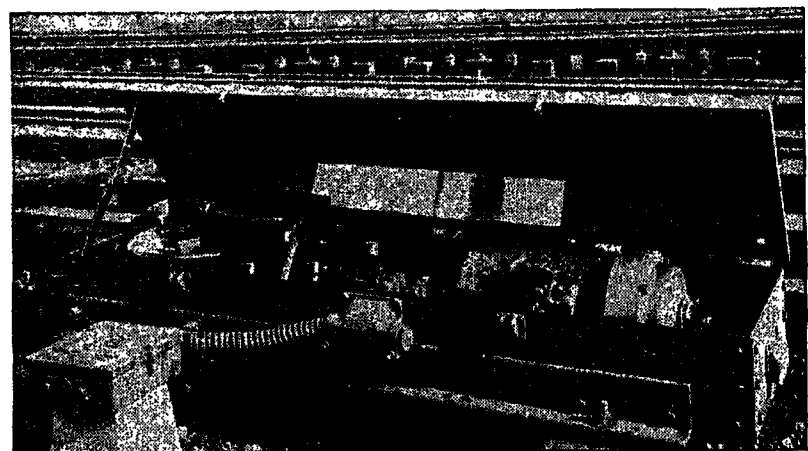


FIG. 3—CAR RETARDER EQUIPMENT IN WATERPROOF ENCLOSING CASE

in their hump yards. The apparatus required, shown in Figs. 2 and 3, consists of a motor and brake coupled to a gear mechanism adjacent to the retarder with remote control to enable operation from conveniently located towers in the freight yard.

The year also was marked by the number of oil electric locomotives and gas electric motor cars put in service by the railroads. Ranging in size from 60 to 150 tons and in power from 100 to 900 hp., oil electric locomotives were successfully used by both railroads and industrial plants.

The popularity of the gas-electric motor car is indicated by the total of 117 cars placed in service during the past year. These cars are rapidly replacing steam trains on the short branch line roads. Industry has also adopted gas-electric units for yard and factory work where overhead trolley wires are undesirable and the old steam driven shift engine is uneconomical.

Distillate fuel has been successfully used in place of gasoline by several companies operating gas-electric trains. This fuel has also been adopted by a large city transit company for use in its gas-electric busses.

The electrification of steam roads has presented the design engineers and manufacturers with many new problems of control. To protect the 11,000-volt single-phase trolleys used by the Pennsylvania Railroad in their new electrification program, from occasional

an average motor size of 1250 hp. Of this total approximately 80 per cent are d-c. machines. This proportion is largely due to the installation of several new continuous mills having individual drive for each stand of rolls.

An unusual installation of interest is the mill drive for the 36-in. reversing universal slabbing mill of the Wheeling Steel Corporation at Steubenville, Ohio. This is the first slabbing mill installed in this country with horizontal and vertical rolls driven by reversible motors. The horizontal rolls are driven by a single armature d-c. machine rated at 7000 hp. continuous, 50/100 rev. per min., 750 volts, and capable of developing a maximum torque of 2,000,000 lb-ft. The vertical rolls will be driven by a reversing motor rated at 1650 hp. continuous, 112.5/270 rev. per min., 750 volts and maximum torque of 212,000 lb-ft.

The control for this equipment is such that only two men are required in the pulpit. The speed and direction of the motors are controlled by means of a foot operated master switch. This switch so controls the two motors that the speed ratio between the two rolls will always be maintained without any necessity for mechanical gearing.

At this same plant there is a wide strip mill installation consisting of a-c. and d-c. motors aggregating more than 20,000 hp.

During the year there were several outstanding installations where steam engine drives were replaced by d-c. reversing motors. The largest d-c. motors in the world are now found driving the big reversing mills of the steel industry.

The Illinois Steel Company in its South Chicago Plant has installed a 7000-hp., 50/120-rev. per min., 750-volt, double unit reversing motor to drive a 40-in. blooming mill. Power for this motor is supplied by a fly-wheel motor generator set consisting of a 5000-hp. induction motor, a 50-ton fly-wheel, and two 3000-kw. generators. A 35-in. blooming mill will be driven by a single unit 6500-hp., 60/140-rev. per min. motor having a similar source of power supply. This plant is also installing a 3500-hp., 50/120-rev. per min., 750-volt d-c. reversing motor on a 32-in. structural roughing mill, and a 6000-hp., 75/140-rev. per min., 750-volt d-c. motor to drive a 28-in. structural finishing mill. A fly-wheel motor generator with a 7500-hp. induction motor, 50-ton fly-wheel, and three 3000-kw. generators will furnish power to these structural mill motors.

The Youngstown Sheet and Tube Company at Youngstown, Ohio, has made several replacements of engine drive by electric motors. A 5000-hp. induction motor will be utilized to drive an 18-in. continuous billet mill. A 2000-hp., 275/550-rev. per min., 600-volt d-c. machine replaced an engine on the finishing stand of a 10-in. skelp mill.

Strip mills are a distinct new development and are gradually replacing the old sheet mills for doing the same work. The new continuous hot-strip mill of the

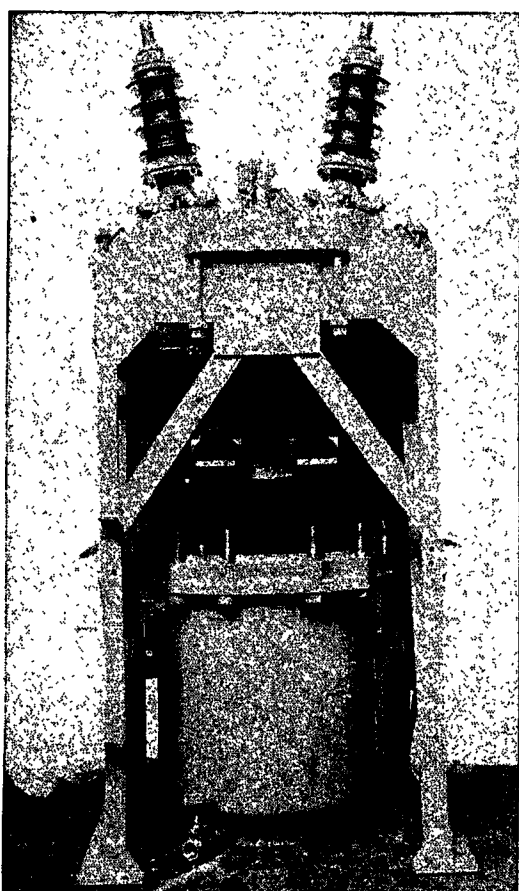


FIG. 4—HIGH-SPEED CIRCUIT BREAKERS FOR P. R. R. ELECTRIFICATION

short circuits and grounds, new high-powered circuit breakers and relays of extraordinary speed were developed. Up to 50,000 amperes at 12,000 volts may be interrupted in a half cycle, 1/50 of a second. Another unusual feature in an oil breaker is the use of magnetic blowout coils to aid in extinguishing the arc. Fig. 4 shows one of these breakers.

In the street railway industry there has been a decided tendency toward lighter and faster motors, lighter car bodies, and improved methods of drive. Dynamic braking, supplemented by air, has come back after many years of discard. Control has been simplified and many new safety features perfected.

STEEL MILL INDUSTRY

The total horsepower of main drive motors installed by steel companies during 1928 reached 212,300, with

American Rolling Mill Company at Middletown, Ohio, is the highest powered of any strip mill yet built. The main rolls are driven by 21,800 hp. in motors; four 3000-hp., and three 2000-hp. d-c. motors on the finishing end, and 3800 hp. in induction motors on the roughing end. This mill purchases 66,000-volt power and has three 4000-kw. motor generator sets to supply direct current for the main roll motors.

The Sparrows Point, Maryland, plant of the Bethlehem Steel Company has made several additions and changes during the year. These changes are in keeping with the intention of the Bethlehem Steel Company to make this plant the greatest steel mill in the world. Fig. 5 gives a general view of the motor room at this plant.

Notable among the additions is the use of 8 synchronous motors totaling 11,750 hp. for main roll drives. This makes a total installation on main rolls of 45 synchronous motors, with an aggregate of 140,750 hp.

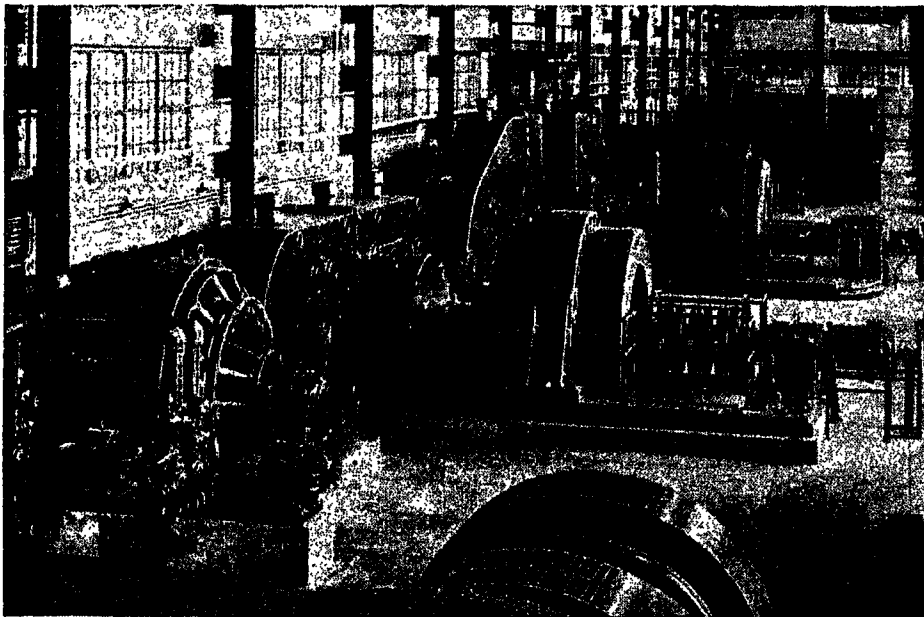


FIG. 5—MOTOR ROOM OF A CONTINUOUS SKELP AND SHEET-BAR MILL IN WHICH ARE INSTALLED DRIVES OF THREE DISTINCT TYPES: D-C., INDUCTION, AND SYNCHRONOUS MOTORS

A control has also been perfected for tying together the 6700-hp. induction motor and the d-c. generator supplying power to the 2600-hp. finishing stand motor. Another new application is applied to the Mesta rotary shears. Each shear is driven by two d-c. motors in series enabling the shears to be run at full speed when the steel traveling at 600 ft. a minute passes through the machine. The speed of the motors synchronized with the speed of the steel enables these shears to cut the steel without an inch variation in the lengths of the sheets.

MATERIAL HANDLING

During the past year industry as a whole was much benefited by the improvement and increase in the number of applications for handling materials electrically. The removal of the human element has in many cases resulted in astounding increases in plant efficiency, while in certain industries the development

of proper equipment for handling odd shapes and sizes, generally conceded forever assigned to unskilled labor, has effected considerable saving.

The year was in general characterized by the application of mechanical handling to a wider variety of uses.

Equipment for handling freight cars was further developed during the year. Fig. 6 illustrates one of the newest type car dumpers, capable of dumping a car a minute. This is being constructed for the New York Central Railroad at Toledo, Ohio. The total electrical equipment aggregates 3000 hp. and consists of both a-c. and d-c. motors with special control by means of variable voltage.

Two other installations now under construction for loading ships, one at New Orleans and the other at Havana, Cuba, are of an unusual type. This equipment will load refrigerating cars on a ship especially

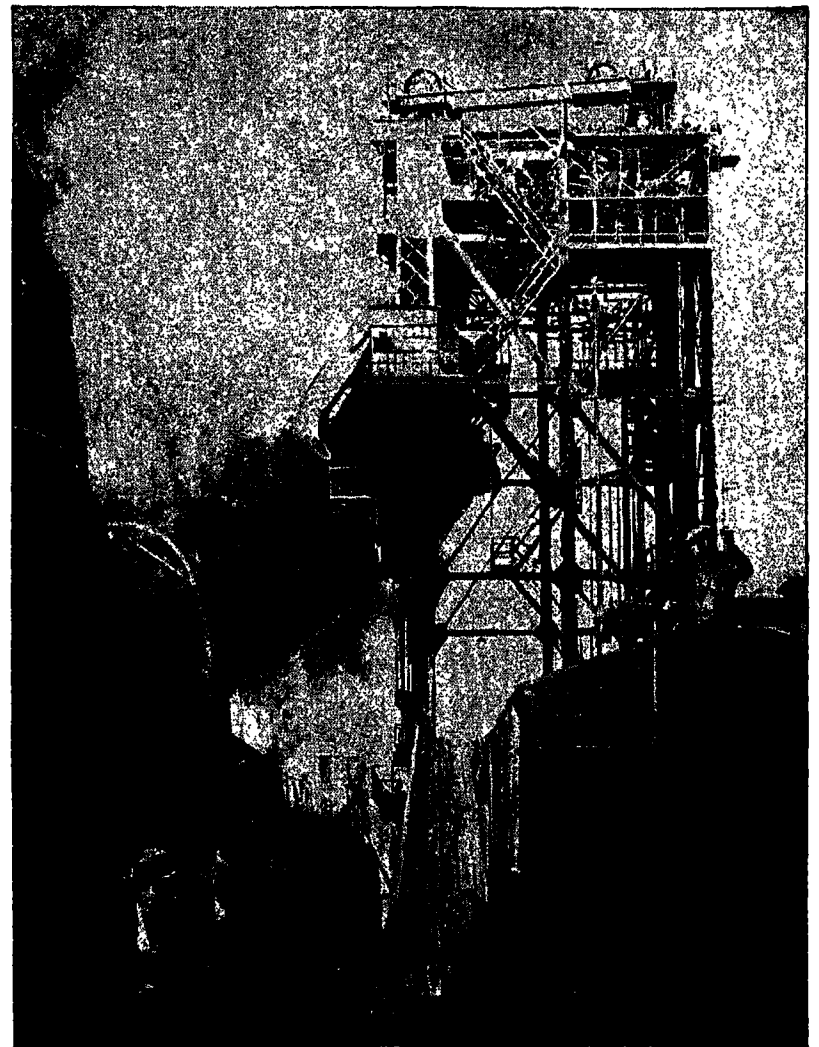


FIG. 6—HIGH-SPEED ELECTRIC CAR DUMPER IN OPERATION. A NEW DUMPER OF THIS TYPE WILL HANDLE 60 CARS PER HR.

designed with tracks to handle about 95 cars. These cranes will lift 165 tons at the rate of 50 ft. per minute and use two 250-hp. totally enclosed mill type d-c. motors for drive. These cranes are the first ever designed for loading and unloading ships with standard freight cars.

Another example of speeding up production electrically is shown in Fig. 7. This 300-hp., 20-ton locomotive with its 14-ton ingot car conveys 300 tons hourly from the soaking pit to the mills. This distance averages 325 ft. and is covered in 20 sec. running time. Needless to say the braking equipment and "dead man

control" must be highly efficient to control safely the four-ton mass of red hot metal.

Prior to 1928 the largest electrical shovel was the 8-cu. yd. or 300-ton shovel. A number of 12-cu. yd. capacity shovels was placed in service during the past year. Due to the extreme fluctuation of current demand, it was necessary to design special equipment



FIG. 7—THIS HIGH POWERED INGOT "BUGGY" OF THE JONES & LAUGHLIN STEEL CORP. MAKES A ROUND TRIP EVERY 48 SEC.

for the drive and control of these shovels. Three motor generator sets, with the generators all differentially wound, are capable of generating 750 kw. The four motors for the various drives aggregate 650 hp. One of these shovels (Fig. 8) recently established a new world's record for material handled when it moved 15,497 cu. yd. of overburden in 24 hr.

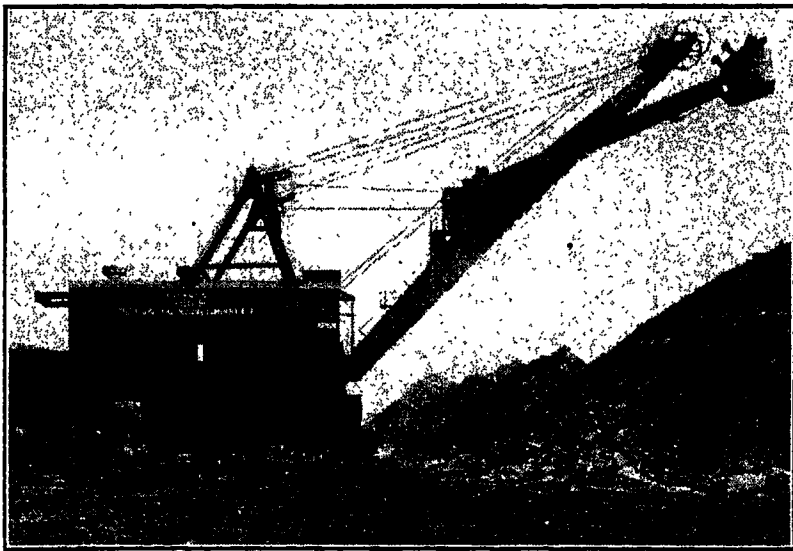


FIG. 8—12-CU. YD. ELECTRIC SHOVEL IN STRIP MINE OF THE ENOS COOK COMPANY, OAKLAND, IND.

Mechanical handling of materials has received considerable increased attention during the past few years in the pulp mills. Whereas the old method of floating pulp sticks to the mill is still in use on account of the obvious advantage of this form of conveying, the mills themselves have adopted modern methods of wood handling. Electrically operated conveyors are operat-

ing successfully in several large pulp mills for handling the sticks from the river to the storage yard, and from the yard to the mill. One installation consists of a log stacker, capable of building stacks 60 ft. high, running parallel to a chain conveyor. Another type of installation uses overhead construction and is able to build stacks 100 ft. high with a capacity of 15 to 20 cords an hour. The equipment used must be of the sturdiest construction to withstand the heavy duty imposed by jammed sticks and blows from falling pieces. Storage of a large quantity of pulp wood is now possible, greatly eliminating seasonal operation in this industry.

A quite extensive application worthy of note is in the automobile industry. General Motors at three of their plants have made large additions and considerable advance in the preparation and handling of foundry sand. Another dirt conveyor, of interest because of its length, was constructed to carry the dirt produced by the lowering of Denny Hill, Seattle, Wash., to Puget Sound.



FIG. 9—INDIVIDUAL MOTOR DRIVES AT THE NATIONAL PAPER PRODUCTS MILL, PORT TOWNSEND, WASHINGTON

The largest belt tripper ever built was constructed during the past year. It is designed for a 54-in. belt and weighs approximately 30,000 lb.

A coal conveyor 2½ mi. long was put into service by the H. C. Frick Co. for transporting coal from the mine to a dock. It is designed to deliver 1800 tons of coal an hour and is driven by 12 wound-rotor induction motors aggregating 2400 hp.

Numerous other improvements in material handling have been made during the year, especially in regard to the method of connecting the drive to the conveyor, as well as the use of anti-friction bearings, gear replacement of pulleys, and other similar refinements.

PAPER INDUSTRY

The paper industry was long since converted to motor drive of the main rolls, but this year has seen the principle pushed still further. Cylinder machines have a larger number of small rolls, baby presses, and

cylinder molds, which heretofore have been driven by the felt carrying the paper pulp. The long, broad belt of high grade felt is decidedly expensive and the practise of using it as a drive necessitated frequent replacements. A new mill at Port Townsend, Washington, eliminated this illogical expense; small motors, Fig. 9, held in extraordinarily exact speed agreement, drive each element.

Carbon pile regulators, which have been successful in the control of single motor paper mills elsewhere, have been further developed to aid in the exact speed regulation of the Port Townsend machines.

sure with back pressures varying from 20- to 40-lb. gage.

CEMENT INDUSTRY

Productive capacity far in excess of normal consumption has caused the cement industry to turn to electricity for economical operation. New plants are universally electrically driven while mechanical drives are rapidly being replaced in the older mills.

Isolated generating plants, utilizing the heat from cement kiln gases, are still popular, although during the

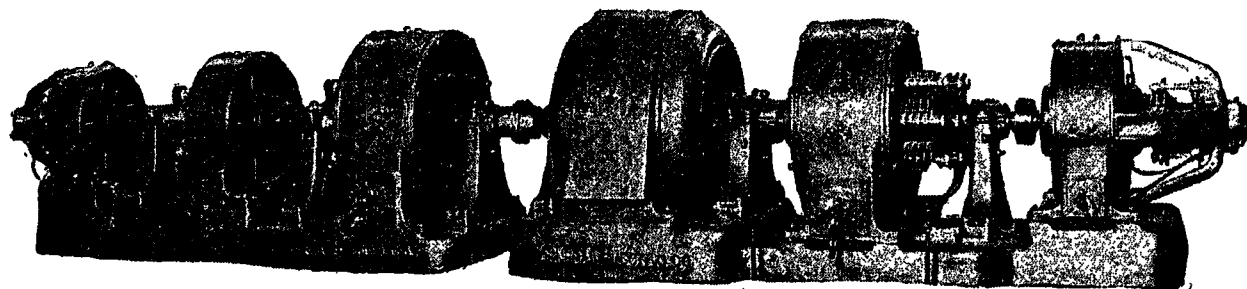


FIG. 10—SIX-UNIT EIGHT BEARING SYNCHRONOUS MOTOR-GENERATOR SET DESIGNED FOR SECTIONAL PAPER MACHINE DRIVE

The Brown Paper Mills Company of Monroe, La., has installed a unique sectional paper machine drive for the manufacture of kraft paper. This paper machine is to make the heaviest paper ever produced on a Fourdrinier machine. The widest range of speed ever attempted on a sectional electric drive, 100 to 1000 ft. per minute, necessitated radical departures from previous methods of operation. Each of the nine motors driving the individual sections of the machine receives its power from a separate generator which forms a part of two six-unit motor-generator sets (Fig. 10). Speed regulation is obtained by automatic control of the generator fields. This feature renders greater torque available in the motors and produces greater stability than would otherwise be possible. This equipment is the only multiple generator control system so far installed on a paper machine.

The manufacture of flat tissue on two small paper machines introduced difficulties in synchronizing the semi-sectional drives on the wet and dry ends. Speed adjustment was accomplished by modifying the synchronous dynamometer speed regulator so that the stator frame of the regulator motor was chain connected to the brush lifting device of one brush shifting motor and its rotor was driven from the same motor through a chain reduction. The stator of the regulator receives its power from a small alternator driven by the motor on the other end of the machine. This equipment is the first of its kind in the country.

A variable speed turbine with reduction gear was an important development in isolated power plant equipment for paper mills. The low speed end of the gear is connected through sheave pulleys to the paper mill and exhaust steam from the turbine is used in the can dryers. Speed can be held within very narrow limits between 65 rev. per min. and 390 rev. per min. on the driven shaft. This unit is rated at 475 hp. at 4200 rev. per min. and operates at 110 lb. gage steam pres-

year several contracts were signed with public utilities calling for an interchange of power. While this exchange provides an outlet for the excess power of these plants, it also places a premium on economics in power generation and mill operation that formerly did not exist.

During the year there were several novel and valuable applications of electricity to the problems confronting this industry.

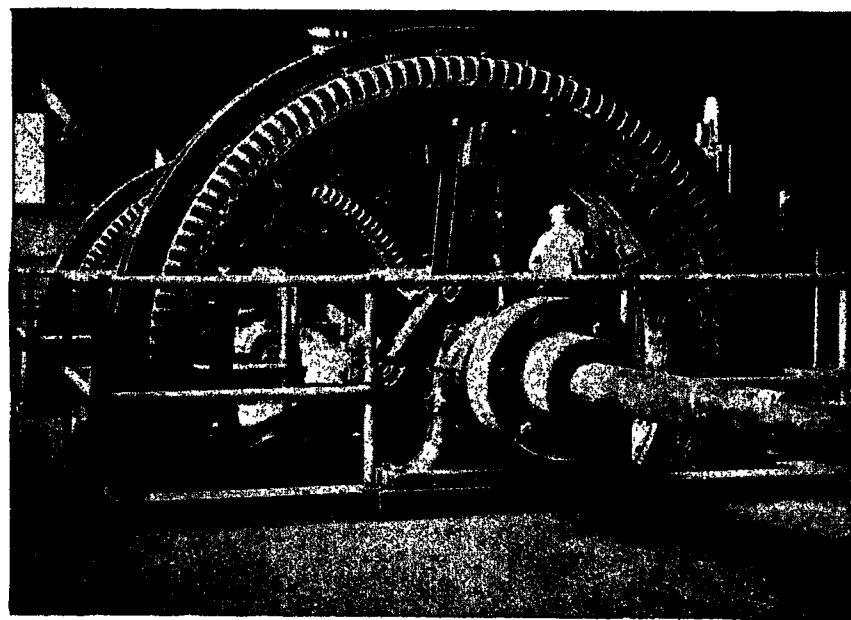


FIG. 11—600 HP. SIMPLEX SYNCHRONOUS MOTORS INSTALLED AT THE MISSOURI PORTLAND CEMENT CO.

Notable among such developments have been several specialized types of synchronous motors designed to provide the high torques necessary for heavy crushing and grinding machinery. New improvements in the clutch and brake of these motors and the application of complete automatic starting control have still further extended the use of the synchronous motor.

Six of these motors, ranging in size from 250 to 600 hp., were installed for tube mill and compartment mill drive in a midwestern plant. See Fig. 11. This is the

first application of the new salient pole synchronous motors with their low starting kv-a. and high torque characteristics. These motors are coupled directly to the mill pinion shaft without the use of a magnetic or mechanical clutch.

Another application of the synchronous motor is on hammer mills. A novel feature of this installation is the overload relay. When the overload is great enough to pull the motor out of step, the relay operates, cutting off the material being fed to the hammer while permitting the motor to regain speed running as a straight induction motor.



FIG. 12—THE LARGEST LOCOMOTIVE UNDERGROUND 30 TON, 532 HP.

Push button control has become almost universal, even for motors of the smaller sizes. One large mill, completed this year, points with pride to the elimination of starting equipment other than push-button controlled, full automatic, circuit breakers of high interrupting capacity. Low starting kv-a. of the motors has made such installations possible; in some cases the motor starts directly across the line.

An important application of specialized control is the automatic blending of dry cement materials as developed in connection with the Fuller-Kinyon System. The Fuller-Kinyon pumps handle the pulverized rock mixture like water and a very ingenious control system for the pumps and valves has been designed. Electrical interlocks and time clock regulation permit almost unlimited combinations for blending the contents of bins or silos to produce a constant quality feed for the kilns.

To keep a uniform flow of material to their kilns, an eastern mill installed synchronous control similar to that used on paper machines. A d-c. generator connected directly to the kiln supplies power to the motor on the kiln feeder. By separately exciting the fields of these machines from a common source, exact speed regulation is obtained.

MINING

The coal mining industry endeavored during the past year to solve many of its troubles by the wider applica-

tion of electricity and the adaptation of more adequate and more efficient machinery.

An outstanding feature of the year was the new mine locomotive, Fig. 12, built for the Pemberton Coal and Coke Company, Bluefield, W. Va. This locomotive, although weighing only 30 tons, develops 532 hp. and will haul a full load of 168 tons up a 1.5 per cent grade at 10½ mi. an hour. This represents more power than the average locomotive on interurban lines and more work than many a steam switcher. This locomotive is constructed of two parts in tandem which, if desired, may be run as two separate units. Electro-pneumatic control and air-brakes are features which are most unusual on this type of locomotive.

The Peabody Coal Company of Chicago has installed in one of its mines a hoist which although not of unusual size is still of interest because of the high rope speed and the number of trips made per hour. The equipment was designed to permit 230 trips an hour from a depth of 282 ft. In order to do this a rope speed of 3300 ft. per min. is required. The total elapsed time of the hoisting cycle is 15.65 sec.

The largest induction mine hoist motor with magnetic control in the country was installed by the Tennessee Coal, Iron and Railroad Company in their mines. The motor is an 1800-hp., 260-rev. per min., induction type hoist motor and a duplicate of two motors previously installed which use liquid rheostats. The magnetic control permits dynamic braking, thus reducing the wear on the mechanical brakes.

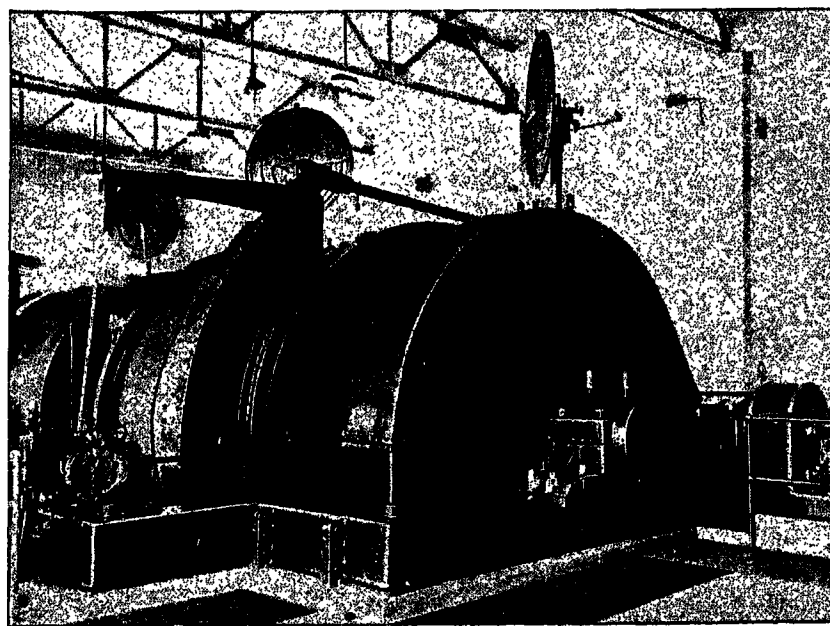


FIG. 13—PIONEER INSTALLATION OF FABRICATED STEEL FRAME INDUCTION MOTOR FOR MINE HOIST SERVICE

Fig. 13 shows the first fabricated steel frame induction motor ever installed for mine hoisting service.

Ore Reduction. The first commercial size plant in this country to utilize the Tainton process, *i. e.*, strong acid and high current density, for the electrolytic reduction of zinc, was installed by the Sullivan Mining Company at Kellogg, Idaho. Current is supplied by two three-unit 4000-kw. motor-generator sets.

The Anaconda Copper Mining Company during 1928 put in operation the largest motor-generator sets ever used in an electrolytic zinc plant. There are four three-unit sets, each rated at 5500 kw.

OIL INDUSTRY

As the oil industry passes the stage of adventuring with its picturesque engine and rig, and becomes more and more a leading industry with an economic problem of conservation, it is marked by the application of electricity to give the most results at the lowest cost. Well drilling has become an affair requiring large capital as several wells have already cost over a quarter million dollars and have reached depths of over 8000 ft. One well in West Texas has been drilled 8255 ft. or 1.56 mi. deep and is the deepest known hole every dug by man. Two 25/65-hp. oil well motors driving a cable tool rig, supply the power for the drilling which is still continuing.

Until very recently it was thought impossible to apply centrifugal pumps to oil pipe lines. A development of suitable high-speed centrifugal pumps which would not emulsify the oil enabled the economic use of electrical drive. A new pipe line 400 mi. long went into service during the past year using this equipment. Forty-four 400-hp., squirrel-cage, 1800-rev. per min., motors drive the pumps in the 13 stations along its length.

ELECTRIC WELDING

Considerable progress has been made in electric welding during the past year. It has been said that electric welding is in a sense a production tool, and for this reason it has been receiving more and more attention from the progressive industrial and construction engineer in his effort to increase output and lower cost.

Only a few of the more important developments in electric welding can be mentioned in this short résumé. One of the most important advances has been the increased size of the electrode used, which in general reduces the time for welding in about the inverse proportion to the size of the electrode.

Another development of considerable importance is the introduction of the new atomic hydrogen method of electric welding, which makes possible the welding of thin metals and alloys that could not be welded before because of the oxidation of the materials by the heat of the arc. This new method introduces hydrogen gas into the arc flame, which gas is broken down into atomic hydrogen by the heat of the arc. This atomic hydrogen effectively prevents oxidation of the materials, so that a satisfactory joint can be obtained. This enables countless small objects to be welded which otherwise would require more expensive methods of union.

The importance of electric welding in the industrial field can be emphasized by the faith of the Ford organization in this type of welding. It is stated that the Ford Company has recently expended over \$100,000,000 for equipment and methods to produce their new model

"A" car, which depend primarily on electric welding. Here electric welding is reduced to an almost automatic process requiring very little personal supervision.

A new process was developed for producing electrically welded railroad ties from scrap rails, which is done entirely automatically and produces a very satisfactory tie at a low cost from scrap material.

One of the largest welding jobs ever undertaken was the welding of a 90-mi. pipe line on the Moke-lumne River project, this pipe being 66-in. in diameter. This pipe was so large that it required two pieces in order to get the required diameter, the pieces being welded by the automatic carbon arc process. The cost of this job was \$12,000,000 for electric welding against the best offer of \$15,000,000 for riveted construction.

A 135-ft. through truss railroad bridge was completed at Chicopee Falls, Mass., with all members electrically

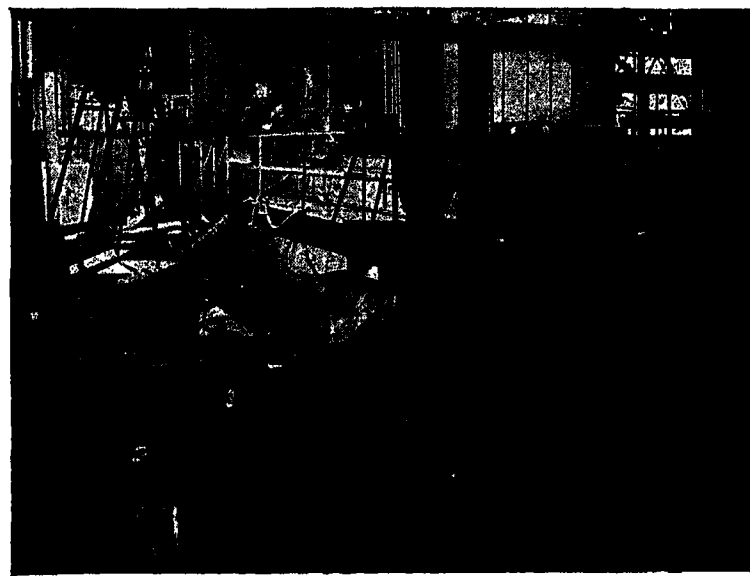


FIG. 14—MULTIPLE ARC WELDING MACHINE FOR AUTOMATICALLY ARC WELDING PIPE UP TO 36 FT. IN LENGTH AND 7 FT. IN DIAMETER

welded. Only two-thirds of the material required for a riveted job was used, and the completed structure cost 20 per cent less than the riveted equivalent. The first commercial building completely electrically welded was finished in Cleveland during the year. This structure used approximately 15 per cent less steel than would be required for riveted construction at a cost considerably less. A factory building, Fig. 15, 145 ft. wide by 550 ft. long, and requiring 1000 tons of steel, was constructed by the electric arc welding process.

The increased popularity of electric welding resulted in the production of a Fordson-driven 300-ampere arc welder for use where there is no other source of electric power. The Fordson not only supplies the power for the welder, but also carries it to and from the work.

During the year a competition for papers on arc welding resulted in an excellent paper entitled "Arc Welding—Its Fundamentals and Economics" written by Mr. James W. Owen. This paper ably presented the present status and the future of this industry.

INDUSTRIAL HEATING

During 1928 the use of electricity for industrial heating has increased rapidly due to the development work of the manufacturers and the recognition of the central stations to the desirability and importance of the load.

Many central stations have established industrial heating departments for the survey and development of the electric heating load.

The manufacturers have developed new equipment during 1928 and the following descriptions cover some of the most important applications.

Electric Stereotyping. The first electric stereotype pot was built and installed in 1925 but it has been during the past year that most of the large installations were made. More than 100 are now in operation, varying in size from 40 kw. for small pots to 360 kw. for large 9-ton pots. The pots make use of an immersion element placed in the lead with automatic temperature control. The total load in many metro-



FIG. 15—FRAMEWORK OF FACTORY BUILDING ASSEMBLED BY ELECTRIC WELDING

politan plants runs from 800 to 1500 kw. connected load for this service. Indications point to the complete electrification of stereotype pots in the next few years.

Silk Moistening. An important application has occurred in the full fashioned hosiery manufacturing field for the moistening of silk before passing through the needles of the knitting machine. Units consisting of an insulated box containing water with felts for the silk to pass through and having electric heating units of 173 watts each are placed so that from 3 to 7 threads are moistened on the way to the needles.

The water is kept at about 160 deg. fahr. and the evaporation of water moistens the felt so that the silk picks up enough moisture to eliminate back winding.

Loads of 990 kw. connected in one plant have been noted and in the Philadelphia district approximately 2000 kw. is in use in this class of business.

Electric Brazing Furnaces. The application of electric furnaces to copper-brazing steel parts together has made possible the assembly in one operation, of complicated structures from simple parts by a strong

alloy weld. This is accomplished by placing copper wire or chips next to joints to be brazed and then heating the assembly in a furnace containing a hydrogen atmosphere to a temperature above the melting point of copper.

The hydrogen performs the function of a flux, as well as excluding air from the heating chamber, in the process of brazing.

Both intermittent and continuous type furnaces are in use for this work and have extensive application in the assembly of refrigerator evaporation shells.

The use of protective gases in other type electric furnaces is recognized as metallurgically beneficial in the heat treatment of various steels and in cases where bright annealing is essential.

High-Frequency Furnaces. Recently the application of the high-frequency induction type furnace to melting and heat treating steel has been given greater consideration. Furnaces are in use for making cast steel in ingot form for production work and for heat treating high-speed steel in liquid baths.

Gray Iron Melting. The application of the indirect arc type electric furnace to the production of synthetic cast iron is a comparatively recent development. Gray iron borings from the manufacturer's machine shop, having a very small market value, are utilized in the production of iron of good physical properties, and the over-all melting cost per ton is less than that for cupola operation. This has opened a new field for development in the iron industry.

CONTROL

During 1928 improvements in design and applications of control have been in keeping with the general trend of the past several years. Although a great many individual instances could be cited, a few general examples will be sufficient to indicate the general trend of the various types of control equipment.

Most of the motor control is now of the definite time accelerating type. A time-current control has developed for d-c. equipment which provides maximum time saving in motor acceleration within predetermined current limits under conditions of light or normal loads and forced acceleration at a predetermined rate where the load is too heavy for the motor to start with the normal accelerating current setting. This equipment is characterized by its simple and rugged construction, the accelerating relays have only one moving part which carries coin silver control contacts while there is only one series coil. This eliminates complicated control circuits and materially reduces maintenance.

Another mechanism for securing definite-time acceleration was developed from the original single contact equipment with a timing ratchet, into a multi-finger form which permits the use of a single relay for actuating in succession a number of contactors.

The conventional form of master switches using segments and fingers has been replaced in the last few

years by the cam operated switches. The past year produced further development of the cam operation, special attention being paid to simplicity of design. An outstanding example of this is a small compact device which was designed to fulfill three purposes, controller, disconnect switch, and overload relay. A complete line of master switches was also produced which required only a few different fundamental cams to obtain a great variety of combination of contact sequence. Still another indication of the trend towards simplified design is in the compact limit switch developed for use on motor driven valve equipment. By means of intermittent gears it is possible to get an adjustment of from 1 to 1365 turns on the valve stem.

Circuit breakers have apparently been accepted by industry to replace fuses wherever there is need of protection. Contrasted to the high powered circuit breaker capable of interrupting 50,000 amperes at 12,000 volts, mentioned previously in this report, the new 110-volt circuit breaker that can be held in the palm of the hand is a mere toy. Yet this breaker has in actual test broken 3500 amperes at line voltage without injury. The smallest units made are for household use, 600 watts, and represent a complete coverage of the electrical field by this equipment.

The Deion circuit breaker was further developed during the year for applications up to 15,000 volts.

Control of motor speed has also received considerable attention during the year. The speed regulator originally designed for control in paper mills has been modified to meet the specific speed problems of a wide variety of industries. In the preceding sections of this report, these applications have been more fully discussed.

Push button control, incorporating simplicity and ruggedness of design without sacrificing dependability of service, is rapidly replacing the cumbersome and complicated control systems of a few years back.

MISCELLANEOUS APPLICATIONS

Rubber Industry. The large expansion of this industry in the past few years has caused engineers to devote their attention to new plants and extensions to present mills rather than the development of new applications. The slow speed synchronous motor has been the predominant type in new installations. Full voltage starting, together with dynamic braking, has been almost universally adopted. All new installations have the thermal, and particularly the thermostatic, type of overload protection. With the wider application of the individual drives more attention has been paid to the type of bearing. The sleeve bearing, with its high starting friction, has been largely replaced by the ball and roller bearings.

Power Applications in Telephone Industry. Power applications in the telephone industry are naturally limited. The drives that are used generally make only small power demands and are commonly rather special

in their nature. Special motors are required for television and sound pictures, with very ingenious speed regulation, but are of too narrow scope for discussion in this report. The development of large capacity filters to eliminate noise producing ripples in the generating current has permitted the application of standard generators for telephone battery charging.

Small Motors. Improvement in design of small motors was apparent during the year. Single-phase motors received a great deal of attention, and the improvements made will be of considerable advantage to various industries.

Single-phase repulsion-induction motors, ranging in size from $\frac{3}{4}$ to 2 hp. at 1800 rev. per min., were produced with a high starting torque and constant speed. Better magnetic utilization of the steel was accomplished in these motors by using square stator punchings with graded slots. Although practically enclosed, improvements in design are such that continuous operation causes only a 40 deg. cent. rise in temperature.

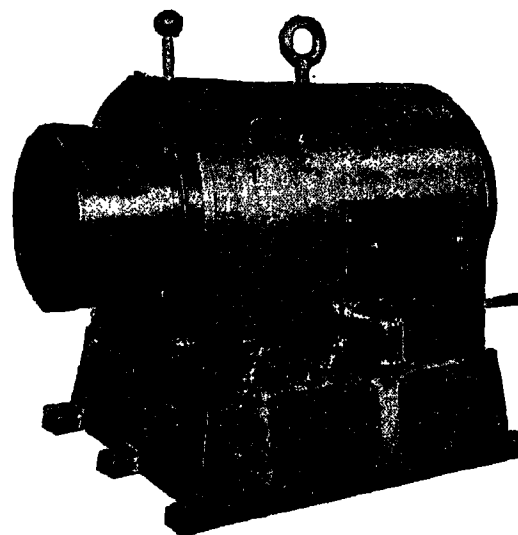


FIG. 16—BRUSH-SHIFTING SHUNT CHARACTERISTICS POLYPHASE MOTOR DESIGNED FOR VARIABLE SPEED SPINNING FRAME DRIVE

Single-phase condenser motors having practically the same efficiency as a two-phase motor and operating at or near 100 per cent power factor were designed. The motor develops even more torque than the two-phase motor, whereas the current required is considerably less.

Recent tests in the textile industry have indicated the desirability of applying the alternating current, brush shifting, shunt characteristic, polyphase motor for obtaining variable speed in the spinning of cotton as well as worsted yarns. The use of this motor, Fig. 16, which permits the best speed over a 3 to 1 range, has resulted in improvement in the quality of the yarn and increased production.

Fractional horsepower motors of new design for use on portable electric hammers combine very light weight with the ability to withstand severe vibration and shock. A full load speed of 10,000 rev. per min. gives 2500 blows of the hammer each minute. This drill is shown in Fig. 17.

Electric Elevators. The development of high-speed, full, and semi-automatic elevators was furthered during the year. Deficiencies affecting the riding qualities of elevators in the automatic control of the rates of acceleration and retardation were removed by the application of a small auxiliary d-c. machine to act upon the



FIG. 17—THIS ELECTRIC DRILL GIVES 2500 BLOWS EACH MINUTE

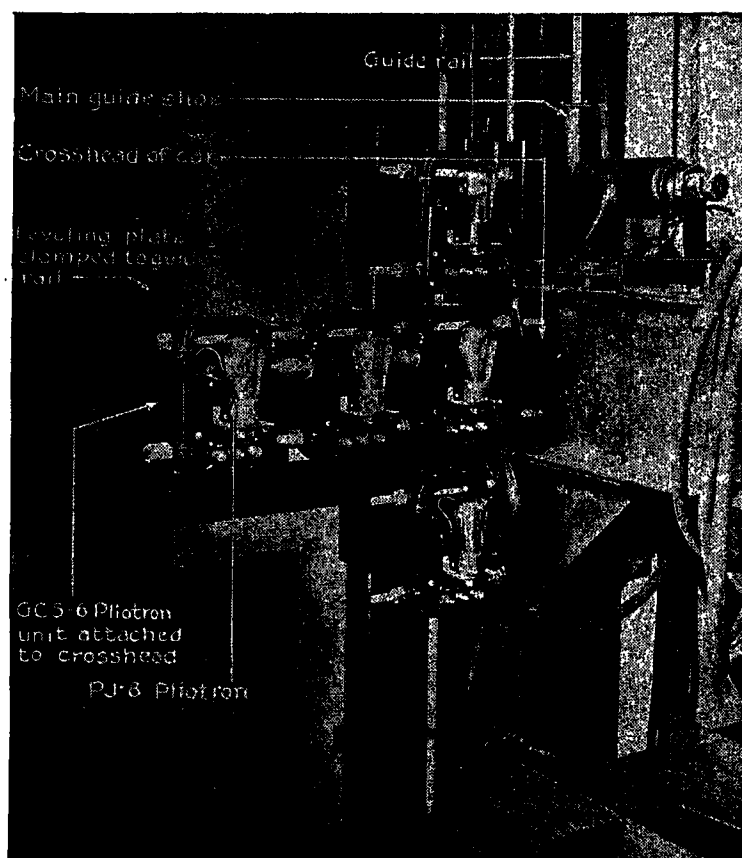


FIG. 18—PILOTRON UNITS AND TUBES MOUNTED ON TOP OF ELEVATOR FOR USE WITH PRE-REGISTERING ELEVATOR CONTROL

generator field of the motor generator set of the generator-voltage type of elevator drive. By this means the acceleration and retardation are caused to begin at very moderate rates, increase to higher rates, and again diminish as the speed change nears completion. The control is shown in Fig. 18.

An automatic levelling system was developed which embodies a radical departure from previous practise. This system utilizes radio-frequency devices wherein the position of the car with respect to the floor controls the levelling speed of the elevator accordingly. The particular advantage of this control is the elimination of all mechanical engagement with its noise and ultimate deterioration, a minimum clearance of $\frac{3}{8}$ in. existing between the parts on the car and the corresponding part in the hatchway.

The most powerful and speediest direct traction motors for elevator service were installed during the year. These motors are rated at 110 hp., with an elevator speed of 450 ft. per minute. The loading is particularly heavy, 10,000 lb., and a precision in floor landing is required in the control which permits a maximum variation of but a quarter inch from exact levelling. This installation is in the new skyscraping Kent Garage of New York. Fig. 19 shows one of these motors.

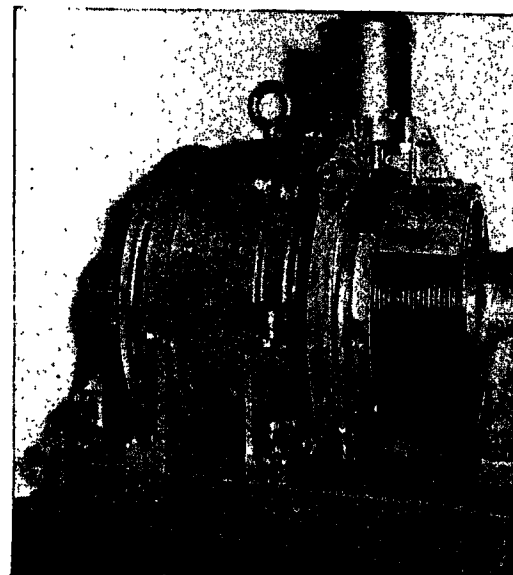


FIG. 19—THE LARGEST DIRECT TRACTION ELEVATOR MOTOR EVER MADE—110 HP.

D-C. Generators. Although not of particular interest in the power field, the new 10,000-volt, 20-kw., d-c. generator developed for the U. S. Navy is noteworthy because of its direct contradiction of the accepted idea that d-c. generators are not feasible above 2000 volts per commutator. Six of these units were built to supply plate current for large transmitting tubes at Arlington, a duty usually performed by rectifying tubes. These generators are bipolar, two commutators in series and two commutating poles. No compensating winding is used. The field frame is of welded steel plate with fabricated feet welded on and has a singularly inconspicuous and non-committal appearance.

Printing. The main advance during the past year in the printing industry has been the increase in the speed of the presses. Where a few years ago 24,000 to 25,000 papers an hour was considered good production, presses today operate at the rate of 60,000 to 75,000 papers an hour. This has meant the application of

higher speed motors in some cases, while in others it was simply a matter of increasing the gear ratio. The horsepower of the motors has increased in proportion, while new improved and simplified methods of control have accompanied the change.



FIG. 20—1000-HP. ROLLER BEARING REDUCING GEARS FOR DANVILLE STRUCTURAL STEEL CO.

Bearings. The old sleeve bearing is being replaced in many instances by anti-friction bearings of various types. Ball, roller, and tapered roller bearings are proving very satisfactory on most type drives.

The largest roller bearing mill type unit was installed in 1928, Fig. 20. This unit is for reducing speed on heavy industrial machinery, and uses helical gears and tapered roller bearings.

The committee is indebted to the following firms with which committeemen are connected or whose cooperation and publications we have made use of in compiling this report:

I. T. E. Circuit Breaker Company
 Philadelphia Rubber Company
 The Commonwealth Edison Company
 Cutler Hammer Manufacturing Company
 The Duquesne Light Company
 Reliance Electric and Manufacturing Company
 D. H. Braymer Equipment Company
 Bell Telephone Laboratories
 Stone and Webster
 Bethlehem Steel Company
 Electric Power Equipment Company
 Lehigh Portland Cement Company
 University of Toronto
 Robins Conveying Belt Company
 Electric Controller and Manufacturing Company
 Philadelphia Electric Company
 Westinghouse Electric and Manufacturing Company
 General Electric Company
 Canadian General Electric Company

Instruments and Measurements

ANNUAL REPORT OF COMMITTEE ON INSTRUMENTS AND MEASUREMENTS*

To the Board of Directors:

The Committee on Instruments and Measurements reports activities for the past year as follows:

1. Revision of Electrical Units
2. Measurement of Core Losses in Terms of Sine-Wave Core Losses
3. Distortion Factor—Definition and Method of Measurement
4. Technique of Temperature Measurement.
5. Measurement of Variable Power and Large Blocks of Energy
6. Dielectric Power Loss and Power-Factor Measurements
7. Measurement of Non-Electrical Quantities by Electrical Means
8. High-Frequency Measurements
9. Remote Metering
10. Shielding in Electrical Measurements
11. Papers
12. Conclusion.

REVISION OF ELECTRICAL UNITS

The progress during the past year of the movement in favor of absolute electrical units in place of those defined by means of arbitrary standards is considered by the Instruments and Measurements Committee to be most gratifying and the actions taken to be epoch making. This progress is recorded in the following report by Dr. H. B. Brooks, Chairman of the Subcommittee on Revision of Electrical Units.

The resolutions on Revision of Electrical Units which were prepared by the Committee on Instruments and Measurements and transmitted to the Board of Directors, through the Standards Committee, were adopted with a slight change at the meeting of the Board in Denver in June 1928. The resolutions cited the discrepancies existing between the international electrical units and the absolute units they were intended to represent, and called on the United States Bureau of Standards and foreign national standardizing laboratories to undertake the researches necessary to eliminate the discrepancies, and to bring about the legalization of absolute electrical units in place of those defined by means of arbitrary standards. Copies of the resolutions were sent to the appropriate committees of the

U. S. Senate and House of Representatives, the Bureau of Standards, and to the national standardizing laboratories of England, France, Germany, Japan, and Russia.

To assist in formulating proposals incorporating a consensus of the opinions held in the United States, Dr. G. K. Burgess, Director of the Bureau of Standards, invited a number of organizations to name members of an American Advisory Committee representing the scientific, industrial, and commercial organizations most directly concerned with electrical measurements. These organizations were as follows: National Academy of Sciences, American Institute of Electrical Engineers, American Physical Society, National Electric Light Association, Association of Edison Illuminating Companies, National Electrical Manufacturers Association, and the American Telephone and Telegraph Company. This American Committee met at the Bureau of Standards on June 16, 1928. After due consideration of the information available regarding the present status of electrical measurements, the American Advisory Committee unanimously adopted the following resolutions:

“(1) Resolved, that in the opinion of this Committee, in view of improvements which are being made in absolute measurements, electrical standards should in future be based upon the absolute system of units.

“(2) Resolved, that in the opinion of this Committee, the functions which it is desirable to have the International Bureau of Weights and Measures undertake in connection with the electrical units, are as follows:

“(1) A central secretariat to arrange for systematic exchange of standards and compilation of results of intercomparisons thus made among the national laboratories.

“(2) A laboratory to which concrete standards representing the results obtained in the different countries may be brought for precise comparisons.

“(3) A repository for international reference and working standards with the necessary equipment so that other standards may be compared with these standards on request.

With the backing of these resolutions, Dr. Burgess attended the first meetings of the (international) Advisory Committee on Electricity, which were held at Sèvres and Paris November 20-22 inclusive, 1928. The timeliness and the importance of the question of the revision of the electrical units are shown by the fact that delegates felt it worth while to come from the far countries of the world, so that the Advisory Committee had a complete attendance of all members. Communications from various countries concerning the electrical units were considered. The cordial spirit and the unselfish aims of the committee are shown

*COMMITTEE ON INSTRUMENTS AND MEASUREMENTS:

Everett S. Lee, Chairman,

H. O. Koenig, Secretary.

E. J. Rutan, Vice-Chairman,

O. J. Bliss,

Perry A. Borden,

W. M. Bradshaw,

H. B. Brooks,

A. L. Cook,

Melville Eastham,

W. N. Goodwin, Jr.,

F. O. Holtz,

I. F. Kinnard,

A. E. Knowlton,

W. B. Kouwenhoven,

E. B. Merriam,

W. J. Mowbray,

T. E. Penard,

R. T. Pierce,

G. A. Sawin,

R. W. Sorensen,

H. M. Turner.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

by the gratifying fact that all the decisions reported were reached unanimously.¹ The committee realized the great importance of dealing adequately with the electrical units, in the light of past experience and present knowledge, and ultimately adopted, by unanimous vote, the following resolutions:

"1. The Advisory Committee on Electricity established by the International Committee of Weights and Measures, considering the great importance of unifying the systems of electrical measurements upon a basis deprived of all arbitrary character, recognizes from the beginning of its first session that the absolute system, derived from the c. g. s. system, may be substituted with advantage for the international system of units for all scientific and industrial determinations and decides to propose its adoption to the International Committee of Weights and Measures.

"2. The Advisory Committee on Electricity, while recognizing fully the great forward steps already taken in the domain of electrical measurements of high precision, does not believe, however, that it is possible immediately to fix with all the necessary and possible accuracy the ratios which exist between the absolute units derived from the c. g. s. system and the international units of current, electromotive force, and resistance, as they were defined by the International Congress at Chicago in 1893 and the London Conference in 1908, and expresses the wish that researches may be carried on toward that end in suitably equipped laboratories, in accordance with a program previously worked out in cooperation with the Advisory Committee on Electricity."

Dr. Burgess was unanimously chosen to report the proceedings of the Advisory Committee to the International Committee of Weights and Measures. The approval of the latter is necessary to put into effect the resolutions of the Advisory Committee. The Committee on Instruments and Measurements regards the action of the Advisory Committee on Electricity as an epoch-making event, and looks forward hopefully to the time when the units of the electrical engineer and those of the mechanical engineer will rest alike upon the fundamental bases, the meter, the kilogram, and the second of time.

MEASUREMENT OF CORE LOSSES IN TERMS OF SINE-WAVE CORE LOSSES

A working committee of the Instruments and Measurements Committee under the chairmanship of Mr. W. M. Bradshaw has been studying for the past year the best way to make core loss measurements on transformers so that they will give accurate "sine-wave" core losses regardless of the wave form employed for excitation. In this connection the working committee issued a questionnaire on the practise of measuring

core losses in transformers. This was sent to fourteen known manufacturers of transformers. Replies were received from ten of them. Of the ten replies, five were from manufacturers of power and distribution transformers, all of whom either recognized the necessity for corrections or actually used corrections. The other five were from manufacturers of instrument transformers or special transformers in which core losses need not be measured. Those who only recognized the general necessity for corrections state that they have available a pure sine wave which remains undisturbed.

As a result of the replies to this questionnaire and from the results of their study, the Working Committee recommended desirable procedure in making core loss measurements to the Instruments and Measurements Committee, which recommendations have been regularly transmitted to the Standards Committee. These recommendations provided for the measurement of core loss of transformers preferably with a sine wave of applied voltage; if this is not practicable, the results obtained with a distorted wave of applied voltage shall be corrected to a sine-wave basis by a suitable method.

Three suitable methods, as follows, have been studied and are outlined in detail in the report:

- No. 1. Standard Core Method
- No. 2. Iron-Loss Voltmeter Method
- No. 3. Flux Voltmeter Method

Methods No. 1 and No. 2 use miniature representative sample cores. In Method No. 3 the correct average voltage is applied to the transformer under test irrespective of the wave form of the applied voltage.

The committee recommended preference for methods utilizing average voltage for correcting core loss results to a sine-wave basis to those utilizing sample cores since the sample may not represent correctly the actual transformer under test.

DISTORTION FACTOR—DEFINITION AND METHOD OF MEASUREMENT

A working Committee of the Instruments and Measurements Committee, under the chairmanship of Mr. W. M. Bradshaw, has studied the definition of distortion factor and method of measurement as disclosed in a report of the French Electrotechnical Commission entitled "Methods of Determining the Distortion of the Voltage Wave of Alternators," and have recommended action concerning these, which recommendations the Instruments and Measurements Committee have regularly referred to the Standards Committee. The definition recommended is the same in substance as proposed in the French report, but differs in form to be in agreement with the form of the present A. I. E. E. definition of Deviation Factor, and is as follows:

The distortion factor of a voltage wave is the ratio of the effective value of the residue, after the elimination of the fundamental, to the effective value of the original wave.

1. A full account of the proceedings of the Advisory Committee on Electricity is given in *Revue Générale de l'Electricité* for Dec. 22, 1928.

A general definition to include all periodic waves was recommended as follows:

Distortion factor of a periodic voltage or current wave is the ratio of the effective value of the residue, after the elimination of the fundamental, to the effective value of the original wave.

Details of methods for measuring the distortion factor of a voltage wave were submitted for use in obtaining data for the establishment of suitable limiting values of distortion factor, as follows:

A. Method of Boucherot using an alternator with a sinusoidal wave and a voltmeter.

B. Method of Belfils using a bridge to suppress the fundamental of the wave to be analyzed, and a voltmeter to read the residue.

C. By oscillogram.

D. By harmonic analyzer.

The method (B) seems at the present time to be the most promising, though further study and development of the apparatus are necessary. This work is proceeding.

TECHNIQUE OF TEMPERATURE MEASUREMENT

The Standards Committee has referred to the Instruments and Measurements Committee the broad question of Standards for the Technique of Temperature Measurement. A subcommittee has been appointed and work is progressing on writing a standard on the technique of temperature measurement. The initial activity will be confined to those temperature measurements included in the present A. I. E. E. Standards.

MEASUREMENT OF VARIABLE POWER AND LARGE BLOCKS OF ENERGY

The subcommittee on this subject, under the chairmanship of Mr. T. E. Penard, is collecting literature from the various manufacturers of meters and metering equipment relative to this phase of the art. The questions of metering large blocks of d-c. energy requiring the use of large capacity shunts in connection with watthour meters and the calibration of such shunts, as well as the use of several low current shunts in parallel with resistance compensated potential connections, are being studied.

A new oscillating meter clamped directly on the bus bars and working on the stray field produced by the currents in the bus is being studied.

DIELECTRIC POWER LOSS AND POWER-FACTOR MEASUREMENTS

The Subcommittee on Dielectric Power Loss and Power-Factor Measurements under the chairmanship of Mr. H. C. Koenig has rendered the following report:

In 1928 Messrs. J. A. Scott, H. W. Bousman, and R. R. Benedict presented a paper before the Institute entitled *A Thermal Method of Standardizing Dielectric Power Loss Measuring Equipment*, (A. I. E. E. Quarterly TRANS., Vol. 47, July, 1928, p. 819). In this paper the authors pointed out the effect of humid-

ity on an air capacitor. As a result of this paper, at least two new investigations along these lines have been made. In one of them, at the Electrical Testing Laboratories, it was shown that a properly constructed air condenser had a power factor of less than 0.01 per cent over a range of voltage up to 20 kv. per inch between plates, and over a range of humidity up to, at least, 85 per cent in clean air. In the other investigation at the Johns Hopkins University, two successful runs of varying humidity and voltage were made, one at a temperature of 77 deg. fahr. and the other at 85 deg. fahr. No air conduction could be detected up to about 90 per cent humidity. At the time of writing further experiments are still in progress.

In the subcommittee report of 1928, attention was called to the development of standards loads for use in checking dielectric loss equipment. Following the successful application of this standard load rated at 20 kv., a similar load has now been developed for use up to 75 kv. This latter load was also used very successfully in making factory inter-checks of dielectric loss equipment. In general, the results of the inter-comparison of dielectric loss equipments were very satisfactory.

As a result of the inter-check made at various factories two conditions have been noticed which are of interest. (1) It has been noted that while most laboratories are in fair agreement as to power factor measurements, there is a decided lack of agreement on current (and, therefore, watt) determinations. It appears that currents of the order of 1 to 10 milliamperes present a somewhat difficult measurement problem. Most laboratories use the same instruments for watt and current determinations, changing the coil connections and using it as a deflection instrument. The laboratories using a bridge method depend on the capacitance of their reference condenser. One of the most satisfactory methods for measuring these currents appears to be a modification of the transformer bridge. This method requires the use of a potential transformer of known ratio and the accuracy of the method depends only on the potential transformer and the capacitance of a condenser used in making the balance. (2) In a number of cases the condition was encountered where the test plate of the reference air condenser was mounted on insulators in such a way that the field from the high-voltage plate to these insulators terminated on the test plate. This sometimes caused the condensers to have power factors as great as 0.5 per cent. In each case it has been found possible to bring the power factor to zero by guarding and shielding these insulators. This condition is quite noticeable with the large open pedestal type condensers used in many of the cable test laboratories.

During the past months there has been considerable discussion regarding the possible effects of the high-frequency discharges occurring in insulations under high stress on measurements of dielectric loss and power factor. While these high-frequency discharges prob-

ably represent energy losses, it is questionable whether or not any of the present methods of measurements include these losses.

The question of dielectric loss and power factor measurements with particular reference to the shielding of both the measuring equipment and the cables under test will be covered in a symposium to be held at the Summer Convention on Shielding in Electrical Measurements. Two papers covering this work will be presented, entitled *Shielding Cables in Dielectric Loss Measurements*, by E. H. Salter and *Some Problems in Dielectric Loss Measurements* by Professor C. L. Dawes.

A new test cell has been developed for determining the insulation resistance, power factor, and dielectric constant on liquid insulating materials. This cell makes it possible to test more rapidly and under better controlled conditions than was previously possible.

Some recent modifications of the Schering bridge have been made which may be of interest. The Schering bridge as ordinarily constructed necessitates the computation of capacitance and power factor of the test condenser from the values of the condensers and resistors in the other arms of the bridge. In order to eliminate the need of these computations, a modified circuit has been developed and used in the construction of several bridges whereby it is possible to adjust the bridge for the capacitance of the standard air condenser, and to make the bridge direct reading in both power factor and capacitance of the unknown condenser. These bridges have also been provided with shields on the various sections to reduce the effect of stray capacitances. In order to readily adjust the potentials of these shields, one public utility company laboratory has had a dummy bridge constructed wherein it is only necessary to set the arms of this bridge to correspond to those of the main Schering bridge in order to establish the proper potentials on the various guard circuits.

The construction of large power-factor correction capacitors has brought about the need for a ready means of measuring the capacitance and power factor of capacitors on voltages ranging from 200 to 4000 volts and with line currents as high as 75 amperes. Several stationary test sets have been constructed for this purpose, which enable power factor and capacitance to be read directly from the scale of a variable self and mutual inductor, utilizing a reflecting dynamometer as a null deflection instrument. Such testing sets are readily adjustable as to both voltage and current. The impedance of the measuring circuit, which must be inserted in series with the condenser, is so low that the drop across it does not exceed 300 millivolts.

MEASUREMENT OF NON-ELECTRICAL QUANTITIES BY ELECTRICAL MEANS

A symposium on this subject was held during the Winter Convention, sponsored by the subcommittee on this subject, under the chairmanship of Mr. Perry A. Borden. The following papers were presented:

Magnetic Analysis of Materials, by R. L. Sanford.

Measurements of Flow by Use of Electrical Instruments, by W. H. Pratt.

Use of the Oscillograph for Measuring Non-Electrical Quantities, by D. F. Miner and W. B. Batten.

Study of Noises in Electrical Apparatus, by T. Spooner and J. P. Foltz.

Electrical Aids to Navigation,² by R. H. Marriott.

The increasing extent of articles in the literature describing the use and application of electrical means to the measurement of non-electrical quantities has made it practically impossible for the subcommittee to compile the many articles on the subject into a bibliography as has been done during the past three years. Hence this bibliography which has appeared annually will not appear this year except as bibliographies are available with the above papers. This growth speaks for the extension of electrical means into fields of non-electrical measurements.

HIGH-FREQUENCY MEASUREMENTS

The subcommittee on this subject, through its chairman Professor H. M. Turner, maintains contact with the radio and high-frequency field through the Standardization Committee of the Institute of Radio Engineers. Under the auspices of this committee, there has recently been issued a preliminary bibliography on high-frequency measurements which is available.

The subcommittee has prepared a list of papers published during the past two years on the subject of high-frequency measurements since the symposium held in May 1927, on the subject. This list is not complete, but it reflects the progress in the art of high-frequency measurements. The list is attached to this report as Appendix A.

REMOTE METERING

Two papers were presented at the Winter Convention under the auspices of this subcommittee, under the chairmanship of Mr. E. J. Rutan. These were:

Telemetry, by C. H. Linder, H. B. Rex, C. E. Stewart, and A. S. Fitzgerald.

Totalizing of Electric System Loads,² by P. M. Lincoln.

The information presented in these papers supplements that reported by the subcommittee in 1928.

The subcommittee is now studying the nomenclature applicable to remote metering.

SHIELDING IN ELECTRICAL MEASUREMENTS

A symposium on Shielding in Electrical Measurements will be held at the Summer Convention 1929, under the chairmanship of Mr. H. C. Koenig. The following papers will be presented:

Shielding and Guarding Electrical Apparatus, by H. L. Curtis.

Some Problems in Dielectric Loss Measurements, by C. L. Dawes.

2. These papers will be published in the A. I. E. E. Quarterly TRANS., Vol. 48, July 1929.

Shielding in Heavy Alternating Circuits, by F. B. Silsbee.

Shielding Short Lengths of Cable in Dielectric Loss Measurements, by E. H. Salter.

Shielding in High-Frequency Measurements, by J. G. Ferguson.

Magnetic Shielding, by S. L. Gokhale.

PAPERS

In addition to those listed above, the following papers were presented at the Winter Convention, New York, February 1, 1929, on Instruments and Measurements:

A New High-Accuracy Current Transformer, by M. S. Wilson.

132-Kv. Shielded Potentiometer for Determining the Accuracy of Potential Transformers, by C. T. Weller.

A Precision Regulator for Alternating Voltage,² by H. M. Stoller and J. R. Power.

The following papers on the subject of High-Speed Instruments and Measurements were presented at the Middle-Eastern District Meeting, Cincinnati, March 21, 1929.

High-Speed Photography in Electrical Engineering, by H. W. Tenney, (available in pamphlet form only).

Oscillographs for Recording Transient Phenomena, by W. A. Marrison.

A New Type of Hot-Cathode Oscillograph, by R. E. George.

Bushing Type Current Transformers for Metering, by A. Boyajian and W. F. Skeats.

Excitation of Current Transformers under Transient Conditions,² by D. E. Marshall and P. O. Langguth.

CONCLUSION

The past year has been one of activity for the Instruments and Measurements Committee. Not all of the present advances in the art have been studied directly by the committee, but these remain for future study and report. Chief among these are the advances in frequency measurement and control, and the remarkable progress in cathode ray oscillography. These and other projects bespeak progress in the measurements field which may truly be called gratifying.

APPENDIX A

A Report of progress in High-Frequency Electrical Measurements as reflected by the literature. A short list of papers published during 1927 and 1928.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS TRANSACTIONS

Two Range Vacuum Tube Voltmeter, Janskey and Feldman, Vol. 47, 1928, p. 307.

Measurement of Surge Voltages, Lee and Foust, Vol. 46, 1927, p. 339.

Measurement of Telegraph Transmission, Nyquist, Shank, and Corey, Vol. 46, 1927, pp. 231 (385).

The Oscilloscope, Bedell and Reich, Vol. 46, 1927, p. 546.

Use of High-Frequency Currents for Control, Boddie, Vol. 46, 1927, p. 975.

Measurement of Mechanical Forces in Elec. Cir., Roper, Vol. 46, 1927, p. 574.

Substitution Method for the Determination of Resistance of Induc-

tors and Capacitors at Radio Frequencies, Burke, Vol. 46, 1927, p. 482.

Condenser Shunt for Measurement of High-Frequency Currents of Large Magnitude, Nyman, Vol. 46, 1927, p. 488.

High-Frequency Measurement of Communication Apparatus, Shackelton and Ferguson, Vol. 46, 1927, p. 519.

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Discussion

F. A. Wolff: I happen to be on the minority side with regard to the question of the substitution, at this time, of the absolute electrical units for the concrete units. There are in fact two separate questions involved. One is whether the present concrete standards are in sufficiently close agreement with the absolute units. The other and more practical question is whether the substitution of absolute measuring apparatus for concrete standards will give as high an accuracy.

Unfortunately, the precision of electrical comparisons is far beyond the limits of accuracy to which absolute measurements can be carried and far beyond the limits of accuracy to which concrete standards can be reproduced. The choice eventually made will be to fix values, as closely as possible, whether by absolute measuring apparatus or by concrete standards.

At this time it cannot be said that the accuracy of absolute measurements has attained the accuracy with which the standard cell or mercury ohm can be reproduced, provided that these concrete standards are constructed on the basis of proper specifications. That has not as yet been done. There was a reaction against setting specifications for the standard cell and silver voltameter because the electromotive force and electrochemical equivalent are characteristic properties of the materials involved. Why then have specifications? Specifications, to my mind, are nevertheless necessary to assure the highest accuracy, especially when the work is done by persons lacking adequate experience.

In connection with previous discussions of this subject, I made a very earnest plea that work on the concrete standards be carried on alongside the new work on absolute standards now going on in various laboratories which without doubt will yield an enhanced accuracy. I am quite sure the same would be true with regard to the concrete standards.

Eventually, as I foresee it, we shall bring about a closer agreement between the values assigned to the concrete working standards and their absolute values. I should like to make that step, however, a little later so that it will not be necessary to make another change in the course of the next five or ten years as further absolute measurements are made. I foresee eventually as this work on absolute measurements is carried to completion that we shall assign a particular value to the standard cell and we shall stick to that for a long time, even though subsequent absolute measurements may show that it is slightly in error, because we shall not want to make another change.

In the same way, I think we shall fall back on a material resistance standard because considerable promising research work has already been done on the causes of variation of resistance standards. I feel confident that even now we are able to construct resistance standards which will retain their values over a long period of years to a closer accuracy than attainable by individual absolute measurements.

With regard to standard cells, a group of cells which has just

been set up at the Bureau of Standards agrees in value to an accuracy of one part in 100,000 with cells which my colleagues and I set up more than twenty years ago. I am sure absolute measurements have not yet attained quite that accuracy.

J. C. Clark: I have a question for Mr. Lee relating to the recommended definition of "distortion factor."

It appears to me that this definition is, possibly, open to objection. To make this clear, let us consider a combined wave having, say, a third harmonic of effective value equal to 500 per cent of the effective value of the fundamental. Under the proposed definition, the distortion factor of the wave would be slightly less than unity. Would it not be better to make the distortion factor the ratio of the effective value of the combined harmonics, other than fundamental, to the effective value of the fundamental?

E. S. Lee: We appreciate Mr. Wolff's position. The substitution of the absolute standards for the concrete standards is not going to take place today. Even those most hopeful for this ad-

vance recognize that there is much work yet to be done before this can be done. But the scientific advantages of such a change are appreciated and the urge to do the necessary work is present. In this there is satisfaction.

It would seem that there has been much time during which specifications could have been adequately made for the standards in their present material form. Perhaps not. However, there is no reason to feel that such standards are to be completely abandoned for there is recognition that they represent the standards of electrical measurements for a most fruitful regime assuring their preservation in form. Time may show their increasing worth as secondary standards. If there are possibilities for their improvement, the realization of such will doubtless still be of benefit.

Referring to Professor Clark's question, we use the effective value of the original wave because we know this value. Also, we are primarily interested in values of distortion factor within, say, 10 per cent or less. The condition cited by Professor Clark would not come within this range.

Iron and Steel Production

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO IRON AND STEEL PRODUCTION*

To the Board of Directors:

Because of the magnitude of the projects and the rapid development that is taking place in certain phases of the iron and steel industry, especially in regard to application of electric power, an annual report of application of electric power to the iron and steel industry must necessarily be a continued story from year to year. These developments are keeping pace with the investigation of the metallurgist, which investigations have resulted in new processes for shaping steel.

While during the past year there have been no new steel plants built, many plants have added to their equipment. During the year of 1928, the steel industry purchased in main drive motors a total exceeding 200,000 hp., the units ranging from 300 to 7000 hp.

It is interesting to note that of this total, approximately 80 per cent are d-c. machines. This is largely a result of the installation of several new continuous mills with individual motor drive for each stand of rolls.

Synchronous motors for driving constant speed mills are increasing in number every year, and during the past year, synchronous motors have been supplied ranging in size from 400 to 5000 hp.

A mill drive of unusual interest which is now being installed is that for the 36-in. reversing Universal slabbing mill at the Steubenville, Ohio plant of the Wheeling Steel Corporation. This is the first instance in this country in which separate reversing motors are used for driving the horizontal and vertical rolls of the mill. The motor which will drive the horizontal rolls is a single-armature d-c. machine rated 7000 hp. continuous, 50/100 rev. per min., 750 volts.

The number of continuous mills having stands individually driven by adjustable speed motors still grows. The largest drive for a mill of this type which has been purchased during the year is that for the 60-in. wide strip mill at the Wheeling Steel Corporation's Steubenville plant. The total continuous rating of the motors on this mill is over 20,000 hp., and d-c. power will be furnished by three 4000-kw., motor-generator sets.

During 1928 the American Rolling Mill Company placed in service a new wide strip mill. This mill is laid out to produce strip material up to about 60 in. wide and is one of the largest strip mills yet installed. The total capacity of the 11 driving motors is 21,800 hp.

*COMMITTEE ON APPLICATION TO IRON AND STEEL PRODUCTION:

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A. O. Cummins,	A. G. Pierce,	T. S. Towle,
Samuel L. Henderson,	F. O. Schnure,	J. D. Wright.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

The manufacturers of wide strips continue to enlarge their manufacturing capacity and apparently the end of their research and development is not in sight. The success of wide strip rolling is in considerable measure due to the accuracy that can be secured through modern electric drives and control equipment using individual motor drive of stands.

Time limit control of acceleration has now been in use on mill auxiliary drive for three or four years and has proved extremely successful.

A mill type motor which completely meets the recent standardization rules of the Association of Iron and Steel Electrical Engineers in all respects as to rating, speed, and dimensions is now in successful operation in a large number of steel mills, one installation of almost 200 motors having been in use for a year and a half with no troubles.

As regards the construction and design of main roll motors, such machinery is now largely being fabricated from rolled steel products by means of arc welding. The magnet frames of practically all of the large d-c. machines are now constructed from rolled steel slabs with feet and lugs welded to them. The stator frames of synchronous and induction motors are fabricated from steel plates and bars welded together, and the rotors of some of the synchronous motors are also being fabricated from plates and slabs.

The use of these fabricated frames has reduced cost and reduced manufacturing time for large electric motors. It also improves commutation and other characteristics, and it has become a definite feature in the new era of steel mill electrification.

The statistics for 1928 show that there was a total of 188 cranes purchased in the iron and steel industry, all having electric drives.

In the field of yard transportation, the Diesel electric locomotive is proving extremely successful in reducing operating and maintenance cost.

During the current year, the Ward Leonard type of control has been successfully applied to blast furnace skip hoists at the Bethlehem Steel Company's Plant at Sparrows Point, and also at the Tennessee Coal and Iron Company in Alabama. Engineers may not generally appreciate the limitations of the hoist equipment of blast furnaces, particularly on those furnaces that have been greatly increased in size in the last few years and are equipped with hoists of the single bucket type. The Ward Leonard control installed at Sparrows Point has quite materially helped furnace filling conditions and made it possible to secure increased outputs on their furnaces.

The electrically operated mud gun is one of the most outstanding developments witnessed by the blast furnace industry in many years. Before describing the

new gun and its operation, a brief consideration of the work previously involved in stopping an iron notch will perhaps aid the reader unfamiliar with blast furnace operation to grasp the significance of the new development.

Tapping holes in the early days of ironmaking were closed by ramming in balls of fire clay with what was known in blast furnace parlance as a stopping hook. The operation was performed by hand and required keeping the furnace off blast for a short period of time. As the size of the stacks was increased, higher blast pressures were used and higher production obtained. This increase in the quantity of molten metal in the hearth and the blast tested the skill of the furnace keeper in stopping back the notch so that the iron would not trickle through after the blast was applied.

The mud gun, which is operated by three mill type motors, enables the operator to stop back the notch without taking the furnace off the blast.

Public utilities are showing increased interest in the possibility of assuming steel mill loads and have entered a few plants supplying a part of their power requirements. Because of the economical use of what have heretofore been waste gases around a steel mill, compe-

tition between the public utility and the steel mill in the generation of power is of course very keen. Apparently the possibility of a public utility entering a steel mill depends not upon its ability to take over existing load under competitive conditions, but the possibility of assuming new loads brought about by increased manufacturing capacity of the steel plant. This phase of the public utility power outlet is comparatively new, but is assuming greater importance each year.

During the current year, the first steel mill interconnected transmission system was placed in service by the Carnegie Steel Company and the National Tube Company in the Pittsburgh District. This transmission system consists of a long span, double-circuit tower line, similar in design to recent public utility practise. It is operated at the present time at 44,000 volts. Five steel mill and coke plant power plants, having generating equipment aggregating 150,000 kv-a., are interconnected. The purpose of this interconnection is to transmit in the form of electric power, excess by-product fuel available at any plant to other plants where a shortage of such fuel may exist. It is an essential feature in the complete utilization of excess blast furnace gas, coke breeze, etc.

Production and Application of Light

ANNUAL REPORT OF COMMITTEE ON PRODUCTION AND APPLICATION OF LIGHT*

To the Board of Directors:

INTRODUCTION

The report of the Committee on Production and Application of Light calls attention to the outstanding advancements and trends in the art of lighting by electricity. Material used in the compilation has been furnished, not only by members of the committee, but by other authorities in various fields.

Production of Light

As was the case a year ago, most of the developments in production of light during the past year have been in the nature of improvements rather than radically new devices or methods.

INCANDESCENT FILAMENT LAMPS

Standard Multiple Lamps. Since the introduction of the standard line of inside frosted lamps, the 50- and 60-watt sizes have both been made with A-21 bulbs but the 60-watt lamp was designed to be 5/16 in. longer than the 50-watt. Subsequent experience has shown that this is not necessary and the 60-watt lamp has been reduced to the same over-all length as the 50-watt, 4-15/16 in. This results in a simplification of manufacturing and packing problems and at the same time permits the use of 60-watt lamps in certain units which at present will only accommodate 50-watt lamps, thereby permitting higher levels of illumination in accordance with modern trends.

The sale of 75-watt lamps, which comprises about 3.5 per cent of the total sale of all multiple burning lamps, has made an inside frosted bulb for this size desirable. Accordingly, the manufacturers announce a 75-watt lamp in an A-23 bulb with the same physical dimensions as the standard 100-watt lamp in the A-23 bulb.

Special Multiple Lamps. The 10-watt 115-volt lamp in the C-9¼ bulb, mentioned in last year's report, has been improved by the addition of flutes to the bulb which makes it more pleasing in appearance and more suitable for Christmas and other holiday decorations. The lamp of same rating in the S-11 bulb has been reserved for sign service and other decorative and miscellaneous purposes.

A new 25-watt lamp of the 115-volt range in a T-6½ bulb was announced. This small lamp in a

tubular bulb 5½ in. by 13/16 in. can be used in small inconspicuous reflectors which are admirably adapted for lighting show cases, paintings, and small signs; it is being used in some of the new types of luminaires for general illumination. (Fig. 1)

Railway Signal Lamps. The following types of lamps have been standardized for railway signal service by the Signal Section of the American Railway Association. They have the C-2 filament form as shown in Fig. 2. This form is rapidly replacing other filament construction.

Street Series Lamps. A notable change has been made in the bulb size of 4000-lumen 15-ampere, 6000- and 10,000-lumen 20-ampere lamps for street lighting service. The bulb of the 4000-lumen 15-ampere lamp has been changed and 10,000-lumen 20-ampere from a long neck PS-40 to a short neck PS-40 bulb. This places the 4000-lumen 15-ampere lamp in the same bulb as the 300-watt multiple lamp and the 20-ampere lamps in the same bulb as the 500-watt multiple lamps. The changes were accompanied by a reduction in the light center lengths of 2½ in. which can be compensated for either by moving the sockets, as is possible in a great many types of equipment, or by the use of a 2½-in. socket extension designed for the purpose. The new designs permit the substitution of machine blown bulbs for hand blown bulbs and have permitted a substantial reduction in the prices of these types.

Street Railway Lamps. A 56-watt A-21 coiled filament inside frosted lamp for operation five-in-series on 525-650-volt street railway circuits has been added to the line of lamps for this service. The new lamp supersedes one of similar rating in the clear S-21 bulb.

Aviation Lamps. The ideas of illuminating engineers on the subject of floodlighting for aviation landing fields crystallized during the year to the point where it was possible to standardize a group of four lamps for this service. These are, the 1500-watt 32-volt T-24, the 3000-watt 32-volt GT-38, the 5000-watt 115-volt G-64, and the 10,000-watt 115-volt G-80 airport floodlighting lamps shown in Fig. 3. One or the other of these four lamps can be used in practically all of the present lighting equipment and it is expected that future projectors will be designed around them in order to utilize to the fullest extent the advantages of high lumen output and efficiency, concentrated light source, and economy in operation and maintenance.

Motion Picture and Sound Recording Lamps. The introduction of motion pictures accompanied by sound required the development of a number of new types of incandescent lamps designed for use both in the studio where the pictures are taken and in the projection apparatus. In the studio, in addition to the standard

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C. J. Stahl,

G. H. Stickney.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

General application	Volts	Amperes	Watts	Bulb	Base	Filament	Rated aver. life (hours)
Night indication, including switch lamps, semaphores, wig-wag highway crossing, and crossing gates.....	3.5	0.3		S-11	S. C.	C-2	1000
	10.	0.25		S-11	S. C.	C-2	1000
	13.5	0.25		S-11	S. C.	C-2	1000
	10.		5	S-11	S. C.	C-2	1000
Day and night indication, including light signals and highway crossing flashing signals.....	10.		5	S-11	S. C.	C-2	1000
	10.		10	S-11	S. C.	C-2	1000
	10.		18	S-11	S. C.	C-2	1000

general lighting lamps, are used three high wattage lamps especially designed for this service. These are the 2000-watt 115-volt G-48 bulb spotlight, the 5000-watt 115-volt G-64, and the 10,000-watt 115-volt G-80, shown in Fig. 4. These latter two lamps are similar in rating to those used for aviation landing floodlights but different in filament construction.

To record the sound on the film and to reproduce it in the theater a small 7.5-ampere 10-volt T-8 bulb lamp, shown in Fig. 5, is used. This lamp projects on the film a fine pencil of light which is varied in accordance with the vibrations of the sound and this in turn variously affects the emulsion on the film. In reproducing the sound in the theater a similar pencil of light is projected through that portion of the film bearing the sound record and into a photoelectric cell. The light of varying intensity which reaches the photoelectric cell modulates the current flowing through it and this modulated current is amplified in order to be fed to the loud speakers. Thus the original sound vibrations are translated to light, recorded upon the photographic film, retranslated to light, then to electric current, and finally back to sound again.

Mechanical Cleaner. The useful life of the very large sizes of incandescent lamps such as the 3000-, 5000-, and 10,000-watt lamps used for airport floodlighting and motion picture studio illumination, has largely been limited by the blackening of the bulb. If the lamps are made in bulbs small enough to fit equipments of reasonable size the bulbs become badly blackened long before the filaments fail. An abrasive powder is now being placed inside the bulbs of these lamps so that after they have become blackened in service they may be swept clean by simply swirling the powder around against the bulb walls.

Colored Lamps. Light's Golden Jubilee, which will be celebrated this year to commemorate the 50th anniversary of the incandescent lamp, will be made more colorful by the use of inside colored lamps, a process developed during the year. By this process the coloring material is sprayed on the inside of the bulb walls instead of on the outside. Thus the coloring material is protected from the weather, is rendered permanent and proof against fading or scratching, and the outside of the bulb is left smooth to retard the accumulation of dirt and permit easy cleaning.

Bases, Sockets, and Adapters. The medium prefocus base mentioned in last year's report has been supple-

mented by a mogul base of similar design but larger dimensions. In addition to the projection lamps to which these have been applied there are now included spotlight lamps, certain types of floodlight lamps, airplane headlight lamps, and airway beacon lamps. They are being used experimentally on locomotive headlight lamps. Equipments provided with the prefocusing sockets designed to accompany the prefocus base have the advantage that renewal lamps may

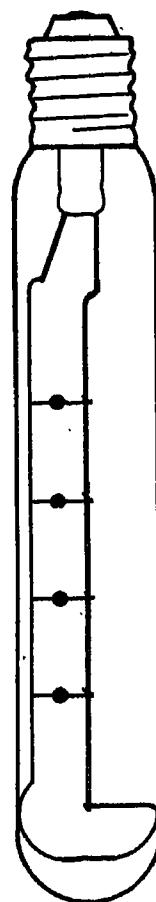


FIG. 1—25-WATT, 110-115-120-VOLT, T-6½ BULB INTERMEDIATE SCREW BASE MAZDA LAMP

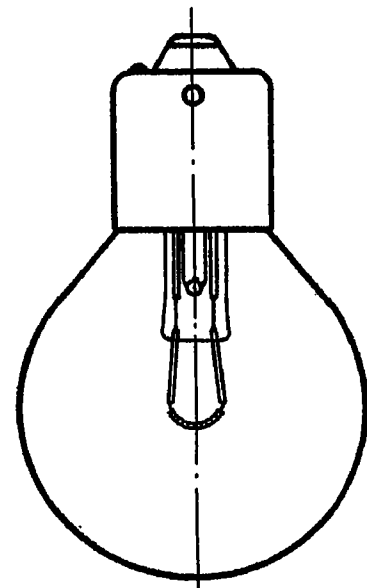


FIG. 2—C2 FILAMENT FORM WHICH IS RAPIDLY REPLACING OTHER FILAMENT CONSTRUCTION

be easily installed and are automatically focused without further adjustment.

Tungsten filament incandescent lamps have been improved tremendously in mechanical strength and ability to withstand abuse, but on the other hand the public has come to expect more and more of them. Lamps are expected to give service today under conditions that would never have been considered a few years ago. To alleviate the worst of these cases a vibration-resisting adapter has been developed which may be installed in the regular lamp socket and serves to protect the lamp. The use of these adapters in

locations where the mechanical failure of the filament is the predominant factor in determining lamp life, will usually prolong the hours in service.

Voltage Standardization. It is common practise to refer to the lighting circuit voltage as "110 volts" but it may surprise many to learn that 110-volt lamps comprised only 8.1 per cent of the total number in the 100—

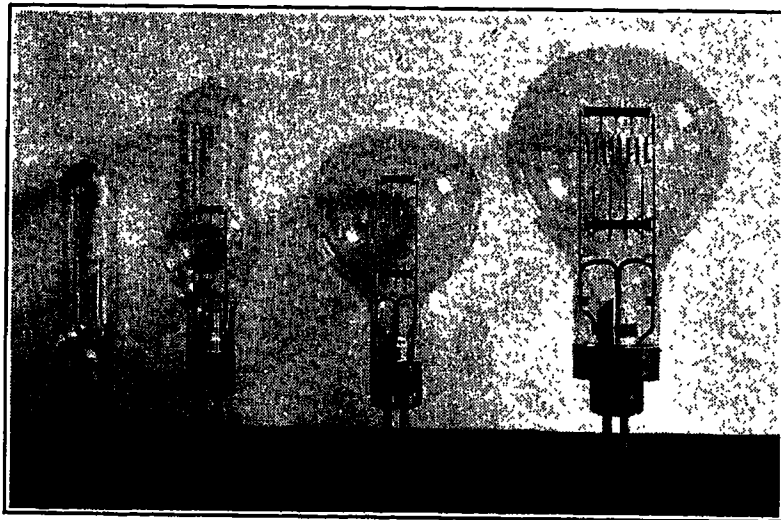


FIG. 3—AVIATION LAMPS
(Left to Right)

1.5 Kw.— 3 Kw.— 5 Kw.— 10 Kw.
32 Volts—32 Volts—115 Volts—110 Volts

130-volt range sold during 1928. Approximately 48 per cent were rated at 115 volts and 39 per cent at 120 volts. The remaining 5 per cent were scattered among the other voltages in that range.

GASEOUS CONDUCTOR LAMPS

Mercury Arc Lamps. To meet the demand for industrial lighting units giving a radiation more nearly



FIG. 4—STUDIO LAMPS,
(Left to Right)

2 Kw. — 5 Kw. — 10 Kw.
115 Volts — 115 Volts — 115 Volts
G-48 Type—G-64 Type—G-80 Type

equivalent to direct sunlight in the effect on general health, mercury arc tubes have been made up in forms identical with those used for industrial lighting but in glass of slightly higher ultra violet transmission. It is possible to build such lamps to meet any specific need in the way of an extended ultra violet spectrum. The practical value of such lamps depends largely on the

recently demonstrated effect that the shortest radiation present in sunlight is apparently also the most effective radiation for most health purposes and that this radiation does not seem to be harmful when used in an amount comparable to that obtainable from direct sunlight. The value as well as possible harmful effects of radiation of a shorter wavelength than this is being investigated.

The rapidly expanding field of application of quartz mercury arcs in both therapeutic and health lighting has brought forth a variety of new types of arc, all of them differing from older designs only in minor mechanical details of construction and appearance. In the past, emphasis has been placed on very clear fused silica of the highest transmission for the very short wavelengths because of the need in some cases of high intensity in the short wavelengths and because in other



FIG. 5—PHOTOPHONE LAMPS, 10-VOLT, 7.5 AMPERE T-8 BULB

cases of sales propaganda on the basis of appearance. The recent emphasis on the importance of the intermediate wavelengths in the ultra violet and the use in many cases of filters absorbing all radiation of a wavelength less than 280 or 290 milli-microns has encouraged a tendency to the use of less clear fused silica.

Neon Lamps. The principal development in high-voltage neon lamps has been in the use of smaller electrode areas than were formerly thought possible and in the construction of neon tube lamps of considerably higher current density than has ever before been used. This has resulted from attempts to use the lamps as landing field beacons and for high-intensity sign work.

New color effects have been obtained through improved filter glasses used as tubing materials, and in a few cases high-voltage discharge lamps have been made using gases other than neon and neon-mercury, but their use has not been widespread.

Hot cathode low-voltage neon tube lamps are being

regularly distributed for use either alone or in combination with mercury vapor tubes for use in box signs, photographic outfits for panchromatic work, and to some extent for beacon work on shipping docks and airplane landing fields.

The negative glow socket type of neon lamp which was mentioned in the 1926 report of this committee has undergone further development during the past year. The present form of this lamp is designed for operation on 115 volts, a-c. circuits and consumes about $\frac{1}{3}$ of a watt, and also for 220 volts, a-c. or d-c., consuming $\frac{2}{3}$ of a watt. The luminous output is of the order of 1/10 cp. Its field of use is primarily that of an indicator or night light. A larger lamp has been developed which will operate on 110 volts a-c. or d-c. and consumes approximately 2 watts, and has a luminous output of the order of $\frac{1}{2}$ cp. The latter lamp is made up using an S-14 bulb and medium screw base.

Induction Lamp. The electrodeless discharge in neon, in the form of an induction lamp, has undergone development during the past year and is being used experimentally as a light source for airway beacons. A 3-in. clear fused quartz bulb incloses the luminous gas. The lamp under operating conditions has a brightness in excess of 40 candles per square cm. and when used at the focus of a 36-in. mirror, a beam candlepower of the order of 500,000 is obtained. Due to the selective emission of the neon induction lamp in the orange red part of the spectrum, this type of light is being tested for visibility in mist and foggy weather. Experiments carried out during the last year have indicated that this particular type of light has considerably greater penetration or visibility per unit of candlepower than has white light. It has been demonstrated that the neon beacon must operate considerably above 100,000 beam candlepower to excel the regular white airway beacon which operates at several million beam candlepower.

A recent test shows no difference between the visibility of light from a neon lamp and light of the same color and horizontal candlepower distribution produced by an incandescent filament lamp with a red glass filter. The comparison of the clear incandescent lamp and the incandescent lamp with red color filter shows that the red filter does not increase the range under any weather conditions. It always reduces the range but there is some evidence that the red filter does not reduce the range as much in foggy weather as it does in clear weather. It was, however, noticed that the flashes of the red beams were generally easier to find among shore lights, especially before the observers had learned just where to look for them.

Television Lamp. Progress during the past year has been made in regard to the flat type of television lamp. These lamps can now be made to have a d-c. breakdown of about 80 volts and will operate at a current density of 10 milliamperes per sq. cm., for several hundred

hours life. The voltage drop across the tube at the above current density is of the order of 70 volts.

Carbon Arc Lamps. A number of types of arc lamps using impregnated carbons has been placed on the market for therapeutic use. While some of these are of the cheapest construction, others are very well made and provided with filtering glasses for proper ranges in the ultra violet spectrum.

Application of Light

INTERIOR ILLUMINATION

INDUSTRIAL LIGHTING

The past year has witnessed an increasing acceptance on the part of production managers of high levels of general illumination. Among the new lighting systems installed were a goodly number in which 15 to 30 foot-candles of general illumination are obtained; in some instances higher illumination values of 40 to 60 foot-candles, over large areas, have been found economical.

Following closely upon the acceptance and installation of these higher levels of illumination is an increasing interest in special lighting for specific jobs. Group lighting, a system in which the lighting units are located with respect to the machine groups, has been adopted in a number of plants, especially those where the location of the machine groups is fairly permanent, and in which the direction of light desired is constant.

The development of group lighting applications requires characteristic distribution curves of light, which are necessary to obtain the greatest utilization over any given area; more and more attention is being paid to control of light to fit these requirements. The year has been truly one in which the important lighting installations may be characterized as "tailor-made" in contrast with the "rubber-stamp" methods of duplicating outlets throughout a work area.

Especially interesting is the tendency in lighting high bay areas, towards the use of higher and higher wattage lamps. Several of the reflector companies have met this demand by redesigning their large high mounting height units to accommodate 1500-watt lamps with a good efficiency as well as 750- and 100-watt lamps.

Notable also is the trend toward dust-proof lighting units, or cover glass appliances, for the 200- to 500-watt equipment. This is in the interest of ease of maintenance in the usual installation, and safety where lighting is used in dusty places. The increasing use of lacquer for coating wood and metal products has brought serious investigation of methods for lighting areas where these products are used, and the lighting equipments considered acceptable. Several large users of lacquer finishes have developed methods for lighting spray booths and spray tunnels, entirely from the outside.

COMMERCIAL LIGHTING

Mention was made last year that installations designed along modernistic lines were beginning to appear.

This tendency has greatly increased. While it is true that this new school of decoration originated in continental Europe, progressive American architects have at once seen its advantages, particularly when applied to the newer forms of American architecture. A more detailed analysis of this trend and its influence is given in a separate news note.

The entrances and lobbies of the new office buildings are striking and generally lighted in such a way as to

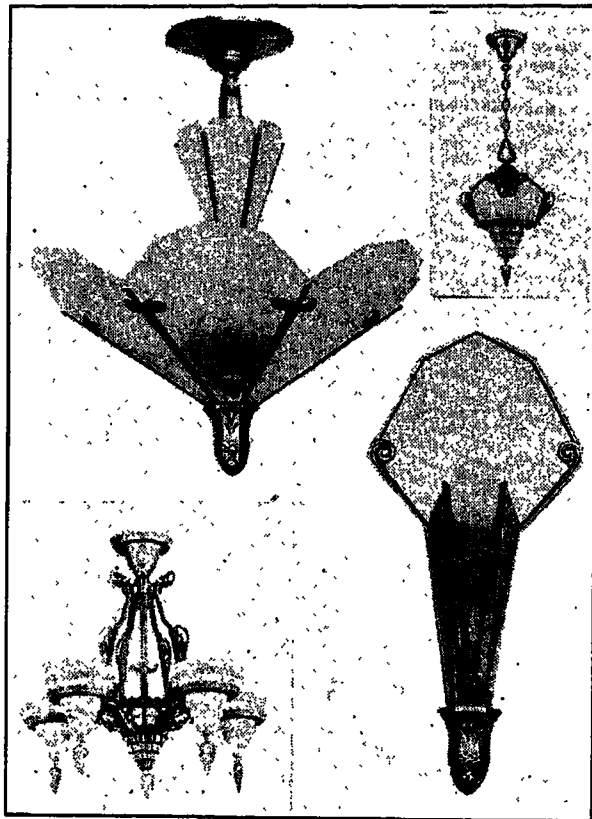


FIG. 6—MODERNISTIC STYLES IN WALL BRACKETS AND CENTER FIXTURES

take full advantage of the potentialities of present day light sources. There has not been much change in the methods of lighting of offices themselves, save a gradual growing appreciation of the benefits of high level, well diffused general illumination.

The merchant is always in search of the new to attract customers, and it is natural that he is one of the first to adopt the new school. Even in the small neighborhood type of store we are finding enclosing units along modernistic lines, although produced in commercial quantities. The distinctive shops have given us some wonderful examples of the use of light for decoration and even the department stores under construction are decidedly modernistic in feeling. On every hand are to be noted show windows with the decorations along modern lines and some very unique applications of lighted window furniture.

RESIDENCE LIGHTING

The modernistic trend in home lighting equipment has made a vast stride in the past year. American manufacturers are offering many varieties of fixtures closely resembling the designs which European artists have been developing. Decorative portables, wall brackets, and center luminaries are designed with pronounced geometric plane surfaces representing, in many

instances, an assembly of rectangles, triangles, or squares of various light colored tints, plain shades, and artistic mixtures. These glass planes not only conceal the lamps from general view but also diffuse the light over a wide area, thereby creating a quality of illumination which illuminating engineers have been striving for years to introduce into the American home for wholesome lighting.

Following a wide development and design in portable decorative units, the domestic manufacturers have developed many new artistic designs of utility equipment for home lighting. Some of these recent types are illustrated in Figs. 6, 7, and 8.

Light Ornaments. A few years ago the use of light simply for decoration was encountered only rarely. Now one scarcely passes a single gift shop which does not display one or more forms of light ornaments. During the past year American manufacturers have developed some very commendable types, a few of which are shown in the accompanying illustrations (Figs. 9 and 10). These use cast figures against lighted background, translucent colored urns, cut crystal figures lighted from beneath, and even translucent

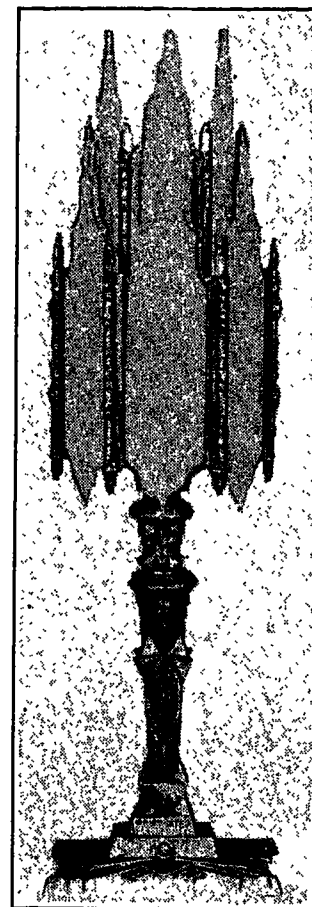


FIG. 7



FIG. 8

porcelain. Other designs are under way and will be on the market shortly. The French manufacturers continue to bring out most pleasing designs, many of which cannot be economically duplicated in America. One of the leading manufacturers has established a local distributor who reports increasing appreciation on the part of the trade.

THEATRICAL LIGHTING

The development of the use of light in the theater during the last year has occurred chiefly in what is

known as the presentation house, the motion picture theater which shows more or less elaborate review numbers in addition to the motion picture. The great chains of theaters that have been taken over by the various large producing companies tend to call for standardized equipment in enormous quantities. Experience has shown that colorful displays which change weekly or twice a week can be considerably aided by elaborate lighting effects. Thus large amounts of good equipment and instruments of better design than was

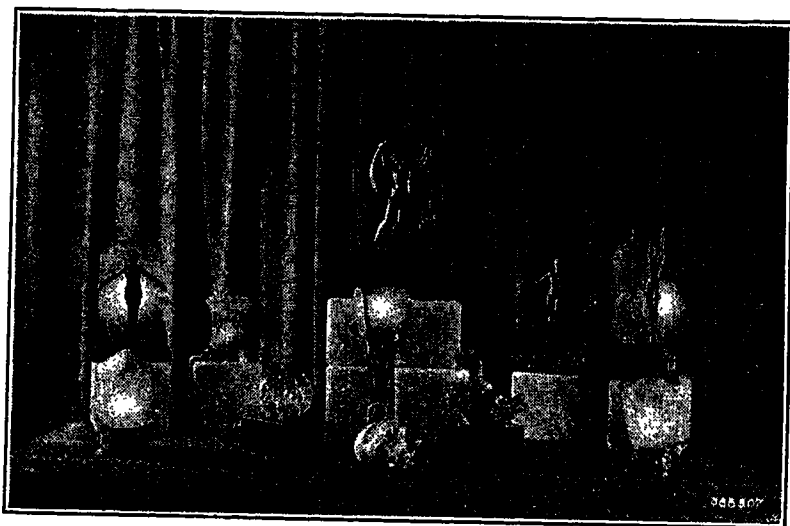


FIG. 9—GROUP OF LIGHT ORNAMENTS OF VARIOUS TYPES PRODUCED BY AMERICAN MANUFACTURERS IN THE PAST YEAR

practical under job lot conditions have been installed in the larger presentation houses.

The nature of the presentations calls for an arbitrary use of light such as has seldom been in the legitimate theater. Designers have been given more freedom and the results are proving that the public demands more extensive use of light than ever before. Managers and architects have begun to give more attention to lighting, and instrument manufacturers and switchboard companies, encouraged by this new market, are endeavoring to perfect their products.

This awakening of the appreciation of the public to lighting effects in the theater is confirming the start that the musical comedy and review producers made some time ago. However, the difference between the means of using light arbitrarily and realistically is so great that the development in the legitimate theater is very slow.

MOTION PICTURE LIGHTING

A census taken about the first of February shows that of some sixty or more pictures in the process of being photographed, approximately 60 per cent were being made with incandescent lamps, an increase from 25 per cent as of July 1, 1928. The general practise of the studios has been to make their sound pictures entirely with incandescent lamps and to restrict the use of other illuminants to the silent pictures.

The Universal Studio has recently completed the filming of the picture "Broadway," taken from the popular New York success of the same name. The largest indoor set ever constructed was used for the

cabaret scene. This scene, together with several others immediately adjacent and really becoming a single large set, was lighted entirely with 4800 incandescent lamps whose wattage totalled 3,900,000. The largest part of this energy was employed in regulation motion picture photographic lighting equipment. However, there were many thousands of lamps of lower wattage employed for decorative effects. This large set is indicative of a general trend throughout all of the studios to employ many low wattage lamps for decorative effects in large and miniature signs, in table lamps and wall brackets, and in automobile headlamps. Lamps are even being operated under water.

The 2000-watt G-48 bulb lamps in the 18-in. parabolic reflector housing and the 5000-watt G-64 bulb lamps in the 24-in. housing continue to be the most popular types of modelling lighting units, while the 1000-watt and 1500-watt PS-52 bulb lamps in high efficiency glass reflectors are extensively used for general illumination. Ten-kw. lamps in 36-in. parabolic reflector units are beginning to be used. One of the manufacturers of the 18-inch reflector unit has shortened the housing to about one-half its former length with the result that 30 per cent more light is emitted when the unit is adjusted for wider beam spreads. Another lighting equipment manufacturer is developing a large glass reflector for general illumination which has an improved distribution and operates the lamp in a more favorable position than the present types. This unit is also being

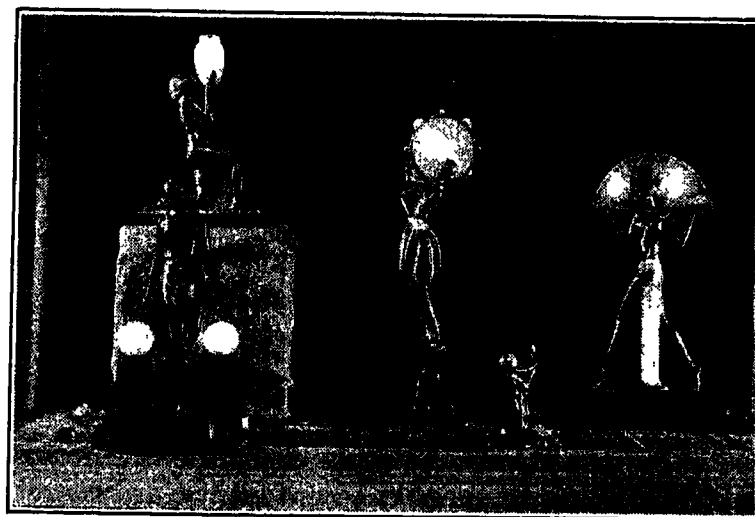


FIG. 10—SOME NEWER DESIGNS OF LIGHT ORNAMENTS OF FRENCH MANUFACTURE NOW BEING USED IN THE UNITED STATES

designed so as to use the 2500-watt PS-52 bulb lamp which is now becoming popular where it is desired to increase the quantity of light without an increase in the number of units.

INSTALLATION STANDARDS

For several years, illuminating engineers have been feeling in an increasing degree the limitation of inadequate wiring as an obstacle to the development of good lighting practise in commercial and industrial buildings.

From a study of the problem it was concluded that this situation and other problems could best be met

by cooperation on the part of central station lighting service bureaus with architects. In formulating a plan, certain officials of the American Institute of Architects were consulted, with gratifying response. Therefore, in the Fall of 1928 a committee of the National Electric Light Association started in on a program of constructive effort. Two courses of instruction for central station lighting service engineers have already been held at which pertinent technical information was reviewed. Distinguished architectural authorities brought out the architect's point of view and indicated methods of approach.

A set of model specification paragraphs has been prepared, to express the adequacy features of wiring so that the illuminating engineer can plan proper lighting. The method of specification contains some new features which facilitate checking up on the wiring construction work.

A third phase of the program is a plan of advertising, to emphasize to architects the importance of good lighting and interest them in cooperation with the lighting experts of the central station companies.

Based on experience in Chicago, the Society for Electrical Development has adopted a simplified method of planning and figuring the lighting installation in accordance with present day standards. This is known as the Franklin Red Seal Lighting Specification, the rules being published in pamphlet form, and provide for all of the ordinary conditions in that field.

A supplementary section suggests the necessity of adequate wiring and recommends wiring corresponding to that specified for the N. E. L. A. architectural activity.

EXTERIOR ILLUMINATION

STREET LIGHTING

Street lighting practise is progressing slowly but at a rate which with a few sporadic exceptions is inadequate to meet the rigorous demands of modern high speed traffic. The average light output of incandescent street series lamps sold during 1928 was 5.8 per cent higher than the output of such lamps sold during 1927 (Report of Lamp Committee, N. E. L. A.). This is one indication of progress since the use of larger lamps suggests improved street lighting. Yet it is the general testimony of the best informed engineers that a marked advance not only in the amount of light produced for street lighting, but also in the skilful application of that

light, is required before street lighting practise may be considered to be abreast of modern requirements.

The outstanding development in street lighting is the increasing recognition of the importance of a comprehensive street lighting plan prepared in coordination with city planning at large and particularly with regard to street traffic problems. The practise of classifying projected street lighting plans by stating the illumination required for streets of different character is also a growing tendency which promises a more definite and scientific treatment in the future.

The value of steel tapes on underground cables is questioned and several manufacturers have introduced cables having no metallic coverings. Others are lead encased but have no covering of magnetic material. This was brought about due to the increasing tendency to use 20-ampere constant current circuits rather than circuits operated at 6.6 amperes.

Occasional High-Intensity Installations. A few notable installations of outstanding character which have been described during the past year are listed in the following table.

These installations are examples of high-intensity street lighting added during the year to the few instances recorded in the 1927 report of this committee. They constitute the exception rather than the rule, but are examples of successful installations meeting the requirements of artificial lighting of important streets.

Two systems of remote control for street lighting circuits utilizing high-frequency carrier-currents superimposed upon the low-frequency current in the poor conductors have been perfected and put into service during the past few years.

One of these systems employs a control current having a frequency of from 35 to 45 kilocycles per second generated by vacuum tube oscillators in the substation and transmitted over the high-voltage power conductors to tuned vacuum tube receivers located at the control centers of the various street lighting circuits. The receiver is tuned to a single frequency and through a time selector relay it opens or closes the street lighting circuit, depending upon the duration of the impulse sent out from the substation. Installations of this system have been made in Schenectady, Rochester, and Glens Falls, New York; Bayonne, New Jersey; Detroit, Michigan; and San Francisco, California.

Location	Extent	Lamps per post Lamp size in.		Mounting height	Spacing
		Lumens	Watts		
Los Angeles (Wilshire Blvd.).....	393 posts	25,000/6,000*	Twin 2000 w. lamps Five 1000 w. lamps	22 ft.	120 ft. apart, either side of street 8 posts per block 100 ft. apart in two rows
Chicago (projected for Wabash Ave.).....	28 posts			28 ft.	
Detroit (Washington Blvd.).....					
St. Louis					
"Intensified" areas.....	†	25,000 to 15,000		26 ft.	
"Intermediate" areas.....		10,000		19 ft.	

*Alternate lamps placed in use respectively before and after midnight.

†Entire project involves relighting of about 650 miles of streets, using about 40,000 lighting standards. Installation about 80 per cent completed in April, 1929.

The second system has been applied particularly to the control of multiple street lamps operated from commercial lighting circuits. The control current is generated by a two-speed motor-generator set in the substation and may have a frequency of either 480 or 720 cycles per second depending upon whether the lamps are to be turned off or on. As in the other system, the control current is transmitted over the high-voltage power conductors. In this system, however, there is a receiver in the base of each lamp post consisting of two tuned relays which open or close respectively a main relay through which the lamp is energized. A recent installation of this system of control has been made in Boston following an experimental installation in New York.

In both of the systems described the provision of a time-delay element removes the possibility of response to lightning or switching surges. Also in both cases an interruption of power does not alter the position of the main relay controlling the lamps, so that upon the restoration of power the lighting circuit is in the same condition as before the failure. The advantages of the carrier-current method of remote control of street lamps arise principally from its use of the power conductors themselves for the transmission of the control impulses. This feature is said to result in the enhancement of reliability (due to the high mechanical and dielectric strength of the power conductors), of flexibility (due to the possibility of transmitting control impulses from a single carrier-current generator over more than one feeder to any desired number of receivers located at any desired distance from the substation) and economy (due to the elimination of separate control circuits).

On the other hand accidental grounds, cross lines, and broken conductors on the power circuit will affect the transmission of the control energy just as they interfere with the transmission of low-frequency power. However, in the event of failure of power to energize the lamps, the lack of control of the lamps does not seem of great consequence.

It is coming to be recognized increasingly that the only thoroughly satisfactory solution of the automobile headlighting problem is to provide street or highway lighting sufficient to permit safe and expeditious transit without employment of powerful far reaching headlights, and at least with depressed headlight beams. In the case of interurban highways the problem of providing fixed lighting is receiving much attention. Where needed, enabling acts to permit counties and villages to provide for highway lighting are being sought. The problem of providing pole lines for highway lighting is, of course, inevitably associated with the problem of rural electrification in general. Progress has been made in reducing the cost of pole lines.

In this connection reference may be made to last year's report of this committee in which there was reproduced a resolution adopted by the Committee on

Street Lighting of the Illuminating Engineering Society, asserting the practicability of so lighting traffic thoroughfares as to permit dimming or depressing of headlight beams. Highway lighting units which give satisfactory service in such installations are illustrated in Fig. 11. Wherever highway lighting employing modern types of units is installed in accordance with good practise, it is claimed that road capacity is increased, night driving is made more pleasant and safe, and property values along the lighted highways are enhanced. Good progress in the installation of fixed highway lighting is anticipated during the next two or three years.

TRAFFIC SIGNAL LIGHTING

In the year 1928 much was done towards standardization of traffic signals. The report of the Committee of the American Engineering Council on Street Traffic Signs, Signals, and Markings was finally completed and has been issued in pamphlet form. This report is very complete and does a great deal to lead to standardization of traffic signal practises.

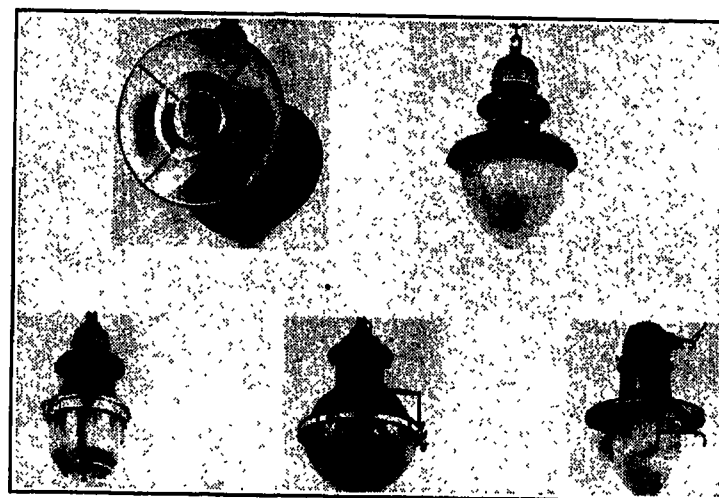


FIG. 11—MODERN TYPES OF HIGHWAY LIGHTING UNITS

In its formative state, this report seemed to favor very strongly the two-color traffic signal, but in its final form the report recognizes that the two-color signal cannot always be substituted for the three-color signals, but it does standardize the meanings of its colors. In addition to this, it publishes designs of safety signs and classifies them, setting aside certain color combinations for restriction signs, other combinations for information signs, and still other combinations for caution signs, all of which will be very helpful if carried out by various cities and state highway departments, since the mere color of a sign will tell the cautious motorist to expect certain information.

Certain states in the Union are taking the matter of traffic signals seriously, with a view to uniformity of laws in the several states. The two most notable examples of this class of legislature are the traffic laws of New Jersey and New York. New Jersey law Chapter 281, Laws of 1928, is a very complete statement of the traffic situation, and is almost in complete accord with the report of the American Engineering Council. This

law was introduced on June 4, 1928, and was approved on July 14, 1928.

On January 8, 1928, New York State enacted Law 46,722 and here again this law is in fairly complete accord with the report of the American Engineering Council. Both of these laws cover not only traffic signals but general traffic ordinances, and these two, together with the "Model Municipal Traffic Ordinance" of the National Council on Street and Highway Safety, published on August 1, 1928, will go a long way toward clearing up the traffic situation and forming a background for various cities and states to enact uniform sensible laws.

Very little change has occurred in traffic signals themselves since these had reached a very high state of development prior to 1928. During the year, however, traffic control apparatus took another step forward in that practically all manufacturers developed control apparatus for a full coordinated movement of traffic. These systems consist of a master timer at Control Headquarters and a secondary control at each intersection, the master timer acting upon the secondaries to control the total period, and the secondaries being capable of controlling, first, the split in time between north-south and east-west traffic; second, the amount of offset to give the coordinated movement; third, the duration of the amber period following the north and south movement; and fourth, the duration of the amber period following the east and west movement.

There was a tendency during the year to push the installation of this class of apparatus along thoroughfares where such timing equipment could be used to advantage. It should be borne in mind, however, that it is impossible to use the coordinated movement of traffic to its full advantage unless the street upon which it is installed has sufficient width to permit the uninterrupted movement of at least one lane of traffic in each direction, the traffic in this lane not to be interfered with by street car loading or by a vehicle getting into or out of a parking space. Its fullest efficiency is thus obtainable only on streets from 60 ft. to 100 ft. wide, or upon narrower streets where there are no street cars or no parking.

Synchronous motor control apparatus also reached a fairly high state of development during the year 1928, the control apparatus becoming much more reliable, and it can now be installed with the reasonable assurance that the timers will keep fairly close in step. Such timers are in the main limited to a single total period; they have the advantage that it is possible to install a system using these timers without interconnecting wires, but it is necessary either to let them run all night or shut them down individually. Such control apparatus finds its best use in smaller cities and along highways connecting the cities with outlying points where it is highly advisable to permit signals to operate twenty-four hours a day.

There was a marked tendency during the year 1928

for the use of curb mounted signals rather than signals installed in the roadway or suspended over the center of the roadway, the most popular signal being the one-way signal mounted on the far right corner. In highly congested areas where double signal indication is advisable, the use of two-way signals with faces 90 deg. apart on the far right corner of the intersection was found to be advantageous.

Portable Flasher. There is being brought out a portable electric flasher designed primarily for traffic warnings where kerosene lanterns have been extensively used. It has, however, many other possible uses in connection with both land and water traffic. Although the initial cost of the beacon is considerably more than that of an oil lantern, its maintenance cost is



FIG. 12—PORTABLE FLASHER FOR DANGER SIGNALS

so much less that in the long run it provides the most economical warning signal. It is estimated that the cost of maintaining an oil lantern is approximately \$50.00 per year, per lantern, where quantities of lanterns are used almost every night and where each lantern must have daily attention for filling, cleaning, etc. The new flasher on the other hand, where one set of batteries will last approximately two months on a basis of continuous burning, will have a maintenance cost of approximately \$10.00 per year.

In addition to this very considerable advantage in maintenance cost, the portable flasher (Fig. 12) has the distinct advantage of the flashing feature, which cannot be obtained with oil lanterns. Traffic and railway authorities agree that a flashing signal is a much better warning beacon than a steady burning light. The weight including batteries is only 16½ lb., which makes it readily portable.

This device requires four standard 6-in. dry cells and a 6-volt., 0.15-ampere lamp. An extra 6-volt lamp is mounted inside the battery housing. The flashover is

of rugged construction throughout and entirely weather-proof.

Automobile Headlighting. Committees of the Illuminating Engineering Society and the Society of Automotive Engineers have been active during the past year considering such subjects as Specifications for Headlamp Mountings, Specifications for the Test of Rear and Signal Lamps, and Comments on the Existing Specifications for test of Headlamps of the dual beam type.

The outstanding achievement during the past year in motor car lighting has been the adoption of fixed focus construction for headlamps. Various investigations have shown that the principal cause of glaring lights has been improper focusing of the lamps. The average car operator understands fairly well how to aim the beams so as to throw the light down onto the road but it seems almost impossible to explain satisfactorily the operation of focusing. With the widespread use of the fixed focus type of headlamp only the aiming operation remains and it is believed that the average car owner will be able to do this reasonably well. This type of equipment is standard on two very large production cars and it will be of interest to note just how great a contribution this type equipment will make towards the reduction of troublesome glare.

In connection with the enforcement activities looking to a better adjustment of headlamps, several states have carried on "Save A Life Campaigns." These campaigns were inaugurated by a proclamation issued by the Governor of the state designating a certain period of thirty days for the campaign and requesting the co-operation of all motorists. Official inspection stations were appointed and in addition to the adjustment and checking of lights, such items as brakes, horns, mirrors, and steering gear were also included. It is the general opinion that these "Save A Life Campaigns" have been very successful in encouraging motorists to keep their cars in better operating condition.

SIGN LIGHTING

The two schools of Electrical Advertising sponsored by the National Electric Light Association in the Spring of 1928 were so successful that it was decided to try out local schools in the geographic divisions. Three of these schools have already been held, New England Division in Boston, Mass., Great Lakes Division in Chicago, Ill., and East Central Division in Cincinnati, Ohio. Others are planned for the Fall.

The Society for Electrical Development, Electrical Advertising Section, is bringing out a Plan Book suggesting methods by which public utilities can stimulate electrical advertising.

The new S-11 sign lamp, supplied in colors and with the intermediate screw base, has been used in some excellent, small spectacular signs where motion and color are featured.

There are several new installations of the so-called "Talking Signs" and one of these was erected for a large

newspaper so the current news could be given out as received.

A smaller sign of this same general type has been developed with gas filled miniature lamps. The message travels across a bank of lamps and this effect is produced by a belt carrying the message punched in it and passing over contacts in the bottom of a mercury bath.

Still another small sign using miniature lamps has been brought out. This consists of a face with a multiplicity of equally spaced openings. The sockets to hold the lamps have two prongs each which can be inserted in the openings and are held by spring contacts. Any message or picture desired can be built up in this way.

Gaseous tube signs are being sold in quantities and quite a number of combined lamp and tube signs have gone in. Some of the most effective of these are painted

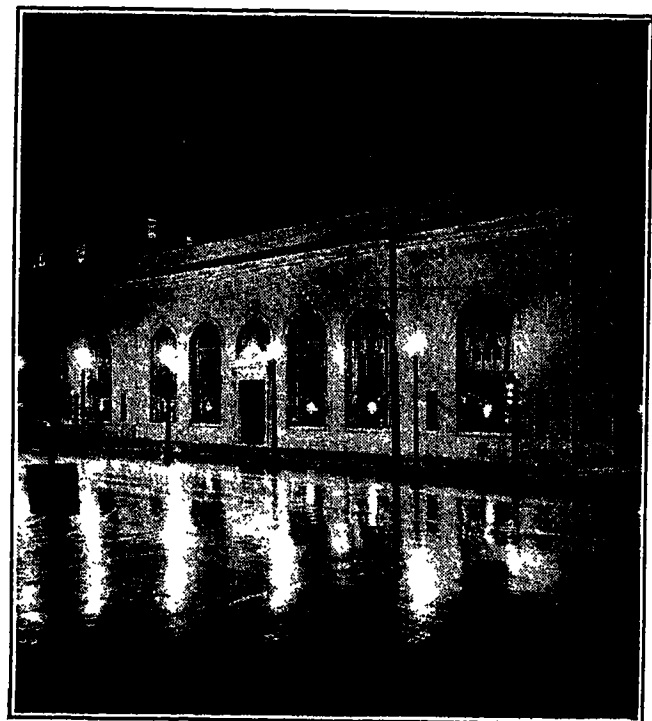


FIG. 13—STREET LIGHTING STANDARDS EQUIPPED WITH SPECIAL REFLECTORS TO DIRECT THE LIGHT TOWARDS THE BUILDINGS

bulletins. The letters may be of tubes, borders of lamps, with angle reflector lighting added if desired. Naturally, a combination sign of this kind has many advantages among which is a better power factor than for the tube alone.

LIGHTING OF BUILDING EXTERIORS

Floodlighting is being used more extensively to bring out the architectural beauty of offices and public buildings at night. In the larger cities new buildings are generally erected with step back construction at the higher levels and these offsets make the use of floodlighting particularly effective.

Architects are also showing a greater appreciation of the value of floodlighting with the result that in some instances the exterior lighting of the buildings is considered at the time the designs for the building are made. Colored lighting is receiving more attention, and the combination of color and motion in what has been called

mobile color lighting is unfolding new possibilities for attractive night displays in building decoration. There is a very decided trend toward the use of colored lighting either with or without motion as this type of lighting has much greater possibilities than the use of plain white light.

Floodlighting of buildings not exceeding 100 ft. in height is frequently being done by means of combination street lighting standards that are equipped with special reflectors to direct the light towards the buildings. (Fig. 13) The ornamental standards are mounted at the curb, and generally use a 1000-watt lamp

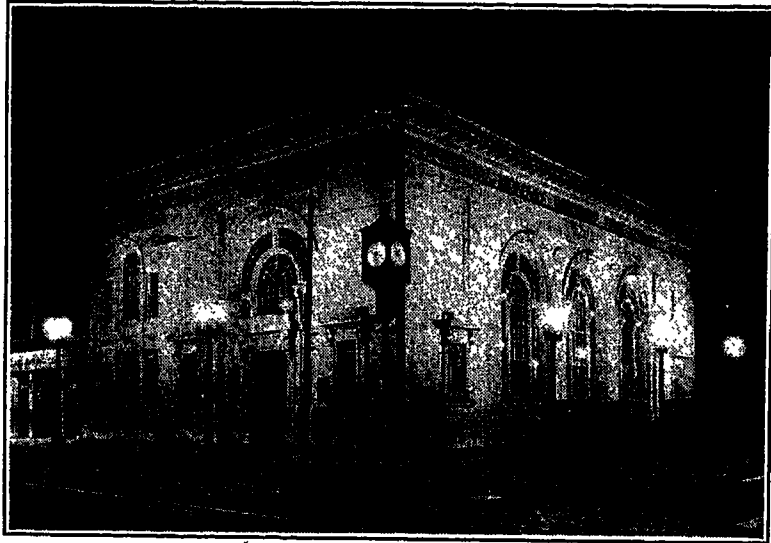


FIG. 14—STREET LIGHTING STANDARDS EQUIPPED WITH TWO LANTERNS IN ORDER TO SATISFACTORILY LIGHT LARGE BUILDINGS

for floodlighting the building, and a 200-watt or 300-watt lamp to light the interior of the lantern and to aid in lighting the lowest portions of the building. In general, this type of lighting produces satisfactory results where the standards are spaced not to exceed twice the width of the sidewalk, measured from building line to curb. For large buildings it is at times found advisable to place two lanterns on one standard in order to obtain a satisfactory amount of light on the buildings. (Fig. 14)

This method of floodlighting is being very extensively used, one Central Station Company alone, the Public Service Electric and Gas Company of New Jersey, having put in service 30 installations of this type during the past year. Among outstanding floodlighting jobs the following are noteworthy:

New Jersey Bell Telephone Company Building at Newark, N. J.; the upper floors and set-backs of this building are floodlighted in white, amber, and red color. The installation has a connected load of 51 kw. and presents a very striking appearance at night. (Fig. 15) In Brooklyn, New York, the E. R. Squibb Building changed over its floodlighting from white light to colored light; in the same city, the new building of the Williamsburg Savings Bank has a floodlighted dome and uses neon tubes in conjunction with the regular floodlighting, the total connected load being about 100 kw. The upper ten floors of the Rand Building at

Buffalo are floodlighted in red, blue, and white lights with a connected load of 144 kw.

Other notable installations are the New York Central Building, New York City, the Fisher Building, Detroit, Cleveland Union Terminal Building, Cleveland, the Chanin Tower Building, New York City, the City Hall, New York City, and the J. H. McClutchey Building, Philadelphia.

LIGHTING OF RAILROAD YARDS

The importance of floodlighting railroad yards is reflected in the increased use of this system during the past year. Sixteen-inch projectors each equipped with a 1000-watt 115-volt, floodlight lamp mounted in banks on towers averaging 75 ft. in height have been used in the majority of installations. Both the unidirectional and parallel opposing systems are used, the method employed depending on local conditions and the opinion of the designer regarding its satisfactory application.

The Committee on Illumination of the Association of Railway Electrical Engineers initiated a study of the photometry of floodlight projectors, but this investigation has been turned over to a sub-committee of the Lighting Service Committee of the Illuminating Engineering Society and National Electrical Lighting Asso-

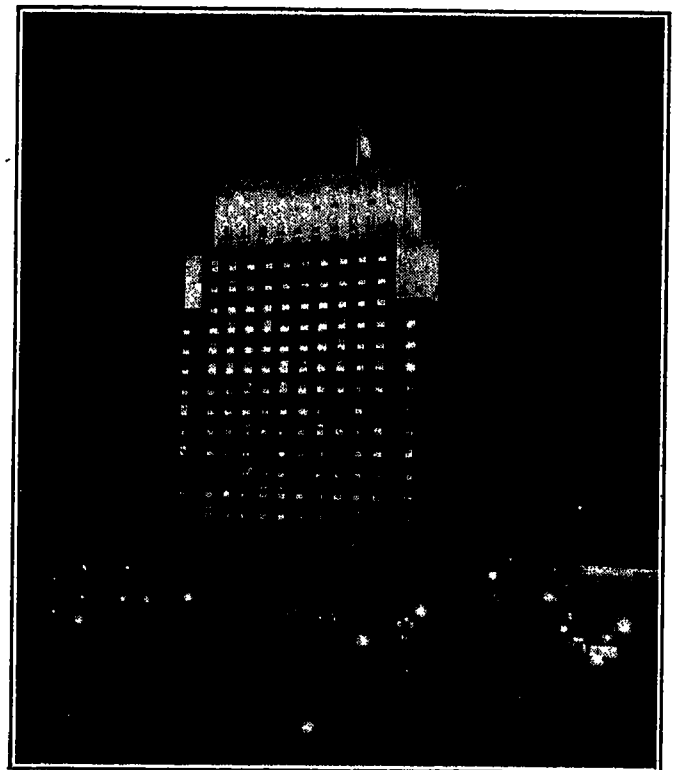


FIG. 15—NEW JERSEY BELL TELEPHONE COMPANY BUILDING AT NEWARK, N. J. THE UPPER FLOORS AND SETBACKS OF THIS BUILDING ARE FLOODLIGHTED IN WHITE, AMBER, AND RED COLOR

ciation. This subcommittee has continued its studies, making a few revisions and additions to the recommended procedure in photometry.

LIGHTING FOR AVIATION

Beacons and course lights have been installed on approximately 9000 miles of the national airways by the U. S. Department of Commerce and about 2000 additional miles will be lighted by the end of June, 1929.

Where course lights are mounted on beacon towers, they are equipped with a red color screen when no landing field is near by and with an amber color screen when a suitable landing area is in the vicinity.

The Airway Marking Committee appointed by the U. S. Department of Commerce to study and standardize a system of national airway marking for the guidance of fliers has recently made public its report. In addition to prescribing definite sizes of letters, figures, and symbols for roof signs, recommendation was made that they be illuminated to an intensity of 10 foot-



FIG. 16—NIGHT VIEW OF HANGAR AT NEWARK METROPOLITAN AIRPORT LIGHTED BY A SYSTEM OF 200-WATT MAZDA LAMPS IN R. L. M. STANDARD DOME REFLECTORS AND STANDARD ANGLE REFLECTORS

candles and preferably 15 foot-candles for adequate visibility at night. For exposed lamp signs, the wattage and color of lamps, together with suitable spacing, were listed according to the size of the sign. (Fig. 16)

Private aeronautical revolving beacons not legally listed on airway routes must be certified by the U. S. Department of Commerce, which also requires that a stationary projector be installed near the beacon with its beam of light pointing toward the nearest airport. This projector must provide a beam divergence not exceeding 6 deg. and a maximum candlepower of two million. A 24-in. searchlight projector with a 1000-watt, 115-volt T-20 bulb airway beacon lamp will usually meet the requirements.

There has been much activity in the past year equipping airports for night flying with a view to obtaining an "A" rating from the U. S. Department of Commerce, which has issued Aeronautics Bulletin No. 16 explaining the requirements in detail. It is particularly interesting to note that high intensity incandescent lamps, such as 1.5-, 3-, 5-, and 10-kw. Mazda lamps have been used as light sources for field illumination in the great majority of installations. Such installations are usually provided with remote control switches, permitting the location of floodlights at a suitable distance from the point of control. The 1.5- and 3-kw. 32-volt lamps are generally used in

projectors of the 24 in. size and the 5- and 10-kw. 115-volt lamps are more often employed in the dioptric lens unit. (Fig. 17)

The U. S. Department of Commerce has suggested the use of an auxiliary green flashing beacon at airports to assist in the identification at night. The details on a satisfactory 5000-cp. unit which will be visible in the upper hemisphere have not yet been completed. The rapid development in the construction of super-airplane for carrying passengers has brought about an improvement in cabin lighting which is decorative. Candelabra fixtures with amber coated lamps are mounted one beside each seat in the cabin. Small enclosing domes are also mounted on the ceiling above each row of seats. Several types of fixed and retractable airplane headlights used for emergency landings at night have been developed during the past year. Most of these headlights, which are usually equipped with a 9-in. reflector, employ the standard 420-watt 12-volt headlight lamp.

The retractable headlight may be operated on the retracted position with beam pointing downward for pick-up and can also be used in any intermediate position to forward, where it is usually held when contact is made with the ground. The fixed headlights are usually stream lights in the wings to reduce air resistance. A smaller headlight with a 6-in. reflector has recently been developed using a 100-watt 12-volt A-19 bulb lamp with intermediate profocused base.

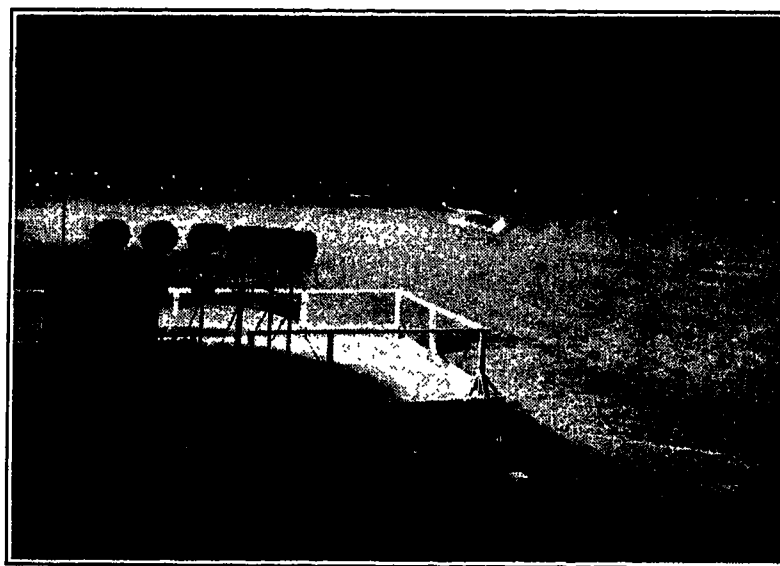


FIG. 17—NIGHT VIEW OF LANDING AREA AT NEWARK METROPOLITAN AIRPORT ILLUMINATED BY 3000-WATT, 32-VOLT MAZDA LAMPS IN 24-IN. AIRPORT FLOODLIGHT PROJECTORS

The subject of airplane headlighting is being studied by a committee of the Society of Automotive Engineers.

LIGHTING FOR NIGHT RECREATION

Under the conditions imposed by the busy American life, it becomes more and more necessary to seek recreation and exercise after the close of the regular business day, which usually means during hours of natural darkness. Coupled with this condition is the fact that many sports are more pleasant in the cooler evening hours and since night lighting becomes increasingly

perfected and less expensive, there has quite naturally been a large increase in the applications of illuminants for night recreation.

Night tennis has been proved to be perfectly feasible and in prolonging the usage of a tennis court, the investment in lighting equipment is much less than the investment in one or several additional courts. Large metal reflectors, now made more highly efficient and more resistant to the elements with the advent of chromium plating, can be suspended at a sufficient height to eliminate glare and to provide on the order of 30 to 50 footcandles over the playing area. A typical tennis court represents a load of approximately 450 kw-hr. per month and from the revenue standpoint, is equivalent to the lighting of ten average homes.

The lighting of golf putting greens has been somewhat extended during the past year and at least one case is on record of the complete illumination of a section of a golf course for practise driving. During the football season, several large universities, particularly in the south, played night games successfully, while night baseball, although not yet entirely practical, is being played on at least one illuminated diamond. Hundreds of outdoor bowling greens and similar amusement areas are successfully lighted, while the past winter saw a number of well illuminated outdoor skating rinks and toboggan slides.

During last summer, night swimming in both outdoor and indoor pools grew in popularity coincident with practical development of a suitable sealed projector available for mounting beneath the water surface,—a practise which adds greatly to the beauty of the pool and, in a large measure, guards against the possibility of accidents or water pollution. Recreation parks now depend to a greater extent than ever on the night lighting decorations. The inside colored lamps and the addition of the 10-watt S-11 bulb sign lamp have been valuable incentives in this application. Unique figures, color combinations, and mass effects of low wattage lamps are taking the place of plaster and wood ornaments and colored paintings.

The floodlighting of ocean beaches has developed, this application being quite similar to the floodlighting of airplane landing fields and using the same apparatus. In these cases there has been considerable employment of the 5- and 10-kw. 115-volt Mazda lamps in both drum projectors and Fresnel lens units. Of more recent date, the 1½- and 3-kw. 32-volt lamps have come into extensive use in similar units. Colored floodlighting of trees and shrubs, of fountains and waterfalls, and the use of colored miniature lamps of the Christmas tree type in beds of flowers, have all added to the usage and popularity of parks and gardens.

Decorative lighting at Christmas time continues to grow and during the past winter, a nation-wide contest sponsored by the Society for Electrical Development brought forth many remarkable installations. The 10-watt multiple Christmas tree lamp and strings of

sockets therefore began to come into quite universal usage for outdoor Christmas decorations. Considering both series and multiple lamps, there were more than 45,000,000 lamp bulbs used in 1928, equivalent to some 9,500,000 40-watt lamps,—a greater lighting load than the entire American output of electric lamps only a few years ago. Activities are under way to extend the possibilities of Christmas decorative lighting to other festival occasions and other seasonal celebrations.

LIGHTING OF BRIDGES AND TUNNELS

Since the opening of the Holland (Hudson River) Vehicular Tunnel, a new standard for the lighting of underground vehicular passageway has been established which is being followed by several similar installations, notably the Zion-Mount Carmel Tunnel in Utah and the Detroit Vehicular Tunnel between that city and Windsor. An item of interest may be recorded, namely, that higher intensities of roadway illumination without glare very materially speeds up the traffic and quite directly returns a greater revenue from the investments in the complete structure. This same fact is now recognized in connection with bridge traffic and it has been quite well recognized that bridge lighting should be on the order of two to three times the intensity of the connecting highways. The floodlighting of bridge structures, especially the approaches thereto, has resulted in considerable beautification of water fronts and incidentally afforded more safety to aviation pilots.

Although not of the man-made variety, the lighting of the famous Natural Bridge of Virginia in mobile color has made this one of the notable bits of night scenery in America. Such applications point the way to the possibilities of making such natural wonders more beautiful by night than by day and more available for enjoyment by the average tourist, who prefers to travel during the sunlight hours and stop for rest and recreation during the evening.

UNDERWATER LIGHTING

Considerable interest has been displayed in the application of electric incandescent lamps to under water illumination. The 1000-watt 115-volt G-40 bulb special diving lamp which is self-contained and designed to be operated directly immersed in the water is standard equipment for all capital ships in the U. S. Navy.

Luminous fountains have been constructed with light projectors mounted beneath water-tight glass plates or with separate water-tight self-contained projectors located in the water or at the base of the fountain jets.

Swimming pools in which the water is the sphere of activity but which have never been properly illuminated due to the reflection of light from the surface, have been illuminated in large numbers by means of lights located in the pool wall beneath the water line. Various types of equipment are now available, some consisting of

lamps mounted behind glass plates, others being water-tight metal units moulded in the pool wall, and still others (Fig. 18) being water-tight self-contained units operating completely surrounded by water but located generally in niches prepared for them in the pool wall.

The underwater lighting of swimming pools is of interest because it improves the cleanliness and increases the safety, and, in general, promotes interest in swimming. In outdoor pools, it is almost compulsory because there is practically no other way to illuminate

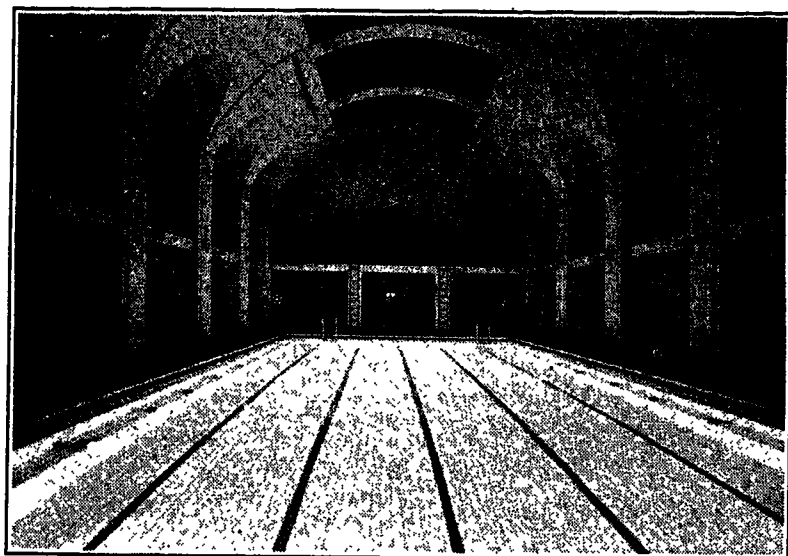


FIG. 18—UNDERWATER LIGHTING OF THE SWIMMING POOL AT HART HOUSE, UNIVERSITY OF TORONTO. LIGHTED WITH 20-AQUALUX 400-WATT UNITS

the pool without using more or less unsightly apparatus overhead.

Fig. 19 shows one of the newest pieces of equipment for underwater lighting service. It is a universal fixture suitable for many types of service and may be installed in many different ways.

ULTRAVIOLET RADIATION

As mentioned under "Production of Light" there has been considerable activity in the field of sources and applications of ultraviolet radiation. Many units employing either mercury or carbon arcs have been placed on the general market. It is too early to state definitely the exact status of the value of these various units, but it appears that when properly handled they will give beneficial results similar to those obtained from sunlight under comparable conditions.

One of the better grade arc lamps employs a screen of Corex D, transmitting between 50 per cent and 65 per cent of the ultraviolet light of wavelength 0.302 μ . This lamp generally employs a therapeutic A carbon for home use but is capable of using therapeutic C carbons giving less visible radiation, but having considerable intensity in the shorter wavelengths.

A great deal of work is under way in the field of development of filters and methods of using the radiation as a preventive as well as a curative method.

PHOTOGRAPHY AND PHOTO-CHEMICAL PROCESSES

The extraordinary progress during 1928 in methods of reproducing sound in conjunction with motion pictures has been made possible in no small degree by improvements in the design of photoelectric cells. Method of recording sound may be classified in two types according as they produce (a) variable density records consisting of bands of different density (or blackness) and constant width, and (b) variable area records of constant density known as "saw-tooth" records. All photographic sound recording methods use the photoelectric cell for reproduction of the sound.

The fundamental principles underlying the photographic methods of sound recording may be stated as follows: Electrical impulses produced by the microphone are converted into light modulations either by means of a glow lamp or with a constant light source in conjunction with a light valve or a Kerr cell. The modulations are recorded inside the perforation area alongside of either the same film on which the negative picture is recorded or else on a separate film. On the positive print used for projection in the theater the sound record appears along one side of the picture area. To reproduce the sound, light from a concentrated filament lamp is projected through the film on to a photoelectric cell. The electrical currents set up by the cell are amplified and led into a loud speaker.

The methods of recording sound have resulted in the introduction of motion picture films having sensitive

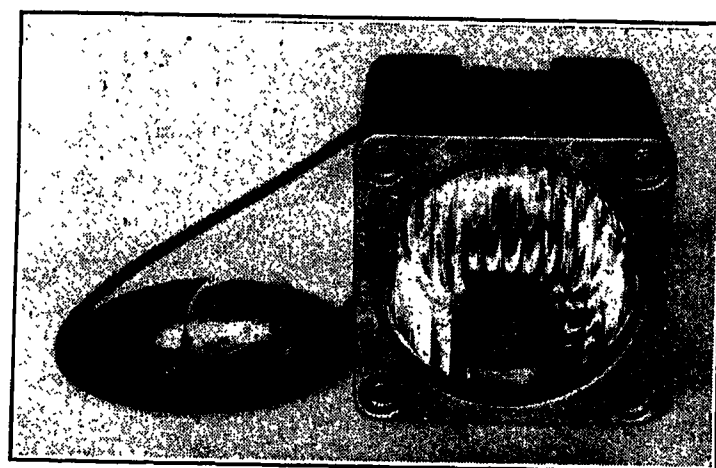


FIG. 19—WESTINGHOUSE UNDERWATER PROJECTOR WITH 30 DEG. HORIZONTAL SPREAD LENS AND 250-WATT G-30 FLOOD-LIGHT LAMP

emulsions particularly adapted to the specific type of sound records. A precise developing technic is also necessary for the processing of sound films with variable density records.

A very thin motion picture film called Ozaphane film is being produced commercially in Europe. It consists of a light-sensitive diazo compound incorporated in a viscose layer. In addition to the diazo compound a coupling agent and a weak organic acid are present. The acid prevents the formation of a dye by the action of the coupling agent on the diazo compound, but if the acid is neutralized by treating the film with ammonia

gas, the dye is formed. Light decomposes the diazo compound so that no dye is formed and the acid is later neutralized. Positive images may therefore be produced directly by this process. The film is much less sensitive to light than the usual silver halide emulsions and therefore requires longer exposures.

INTERNATIONAL COMMISSION ON ILLUMINATION

The last year was a very important one for the U. S. National Committee, inasmuch as the American meeting of the International Commission on Illumination was held then. The committee was fortunate in enlisting the good offices of the Illuminating Engineering Society in making arrangements for this meeting. The meeting was attended by about sixty delegates from twelve different nations and was held in Saranac Inn, New York, September 22-28 inclusive.

Subsequent to the meeting, the delegates were taken on a tour which included New York, Boston, Philadelphia, Cleveland, Detroit, Chicago, Niagara Falls, concluding at Toronto where the delegates attended the annual convention of the Illuminating Engineering Society.

The commission has some fifteen technical committees, all of which met at Saranac Inn and considered recommendations and reports from the various national committees with a view to formulating recommendations for adoption by the Commission.

The technical papers at this meeting covered a very wide variety of subjects, the practical details of lighting practise receiving a very large amount of attention. Discussions of street lighting, automobile headlighting, factory and school lighting, residence lighting, aviation field lighting, show window lighting, were of a very thorough-going and valuable character and were interspersed with other discussions of more specialized topics of interest to the photometrists, etc. To the other technical committees for which the United States National Committee exercises the secretariat were added two new ones, *viz.*, the Technical Committee on Lighting for Aerial Navigation and the Technical Committee on General Practical Applications of Illumination.

The proceedings of the meeting which are now being printed will make a volume of upward of 1500 pages and constitute a very notable summary of the present state of the art and science of illumination as it exists not only in this country but throughout the world.

The next meeting of the Commission is to be held in 1931 in England.

The committee wishes to acknowledge the cooperation of the following men not members of the committee: E. W. Beggs, H. S. Broadbent, R. E. Carlson, R. W. Cost, C. Dick, S. G. Hibben, H. C. Rentschler, Geo. H. St. John, and R. L. Zabour of the Westinghouse Lamp Company; R. E. Farnham and James M. Ketch of the National Lamp Works of the General Electric Company; A. L. Broe, E. B. Fox, A. L. Powell, and G. F. Prideaux of the Edison Lamp Works of the General Electric Company; C. A. B. Halvorson of the General Electric Company, West Lynn, Mass.; H. P. Gage, of the Corning Glass Works; Loyd A. Jones of the Eastman Kodak Company; K. W. Mackall of the Crouse-Hinds Company; R. D. Mailey of the Cooper Hewitt Electric Company; S. R. McCandless of the School of Fine Arts, Yale University; and C. H. Sharp of the Electrical Testing Laboratories.

Discussion

F. C. Caldwell: One part of this report deals with the lighting of building fronts. The importance of this is due to the fact that in a modern well-lighted business street much more light is used than is needed for safety in traffic, and the additional electric power is justified in order to increase the attractiveness of the street. It has been well established that the best way to do this is to increase the illumination on the building fronts, thereby lighting up the whole street rather than only the pavement.

In this connection the use of asymmetric refractors designed to throw the light on the buildings across the street may be mentioned. With the ordinary symmetrical lighting unit, there is a bright spot on the building adjacent to the lamp, and opposite the lamp, and then comparatively low illumination up to the next unit. What is needed is a fairly uniform illumination. If a refractor is used which takes some of the extra light that is thrown on the building adjacent to the lamp, and throws it across the street on to the buildings on the other side, better results are obtained.

This report gives little consideration to the enormous increase in the use of the gaseous tube signs. This is certainly one of the notable features of the past year and perhaps should have somewhat more emphasis than is given here.

L. M. Duryea: In Southern California, we find universal use of neon tubes for sign lighting. When we compare this with New England, where there is comparatively smaller use of neon, we wonder if there isn't a very direct relationship between the use of neon tubes and climatic conditions. When neon tube lighting can be made to withstand severe climates, and when static condensers are installed across the terminals of the high-voltage transformers inside the signs, by the manufacturers, to aid in the important power-factor problem of these signs, then possibly the use of neon tubes in the East will become as universal as it now is in the West. Until these things are done, it is evident that the use of neon in the East will be greatly retarded. The incandescent lamp signs will continue to offer very keen competition in spite of the greater novelty and better advertising value of neon-tube display.

Applications to Marine Work

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO MARINE WORK*

To the Board of Directors:

The activities of the Committee on Applications to Marine Work this year were devoted chiefly to the consideration of future revisions in the Marine Standards (A. I. E. E. Standard No. 45) and in further efforts to induce the U. S. Steamboat Inspection Service to arrange for proper recognition and classification of the electrical engineer on shipboard. Owing to the few active matters for consideration by the committee, and the unusual activity in new marine construction placing a large demand upon the time of most of the committee, the meetings of the committee were curtailed.

For certain reasons not pertinent to this report, the committee's progress with the U. S. Steamboat Inspection Service has been extremely slow, even though the committee has done considerable constructive work to assist in bringing about a solution. Apparently, certain obstacles have been encountered which will have to be economically dispensed with if our efforts are to succeed; however, the committee is hopeful of a final solution which will obtain for the electrical engineer the recognition and classification which he deserves. It is recommended that the committee pursue this activity with unceasing efforts and possibly through other channels.

*COMMITTEE ON APPLICATIONS TO MARINE WORK:

W. E. Thau, Chairman,	Wm. Hetherington, Jr.	Wm. H. Reed,
Edgar C. Alger,	H. L. Hibbard,	Edgar P. Slack,
R. A. Beekman,	A. Kennedy, Jr.,	H. M. Southgate,
H. C. Coleman,	J. B. Lunsford,	Oscar A. Wilde,
E. M. Glasgow,	E. B. Merriam,	J. L. Wilson,
H. F. Harvey, Jr.,	I. H. Osborne,	R. L. Witham,
C. J. Henschel,	G. A. Pierce,	

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

The past year has seen the following major marine activities in which electricity has contributed its full share:

1. The placing in service of five turbine electric drive U. S. coast guard cutters. These ships use the dual-drive system for the auxiliaries.
2. The placing in service of the 18,000-shp. twin screw turbine electric drive passenger vessel, S. S. *Virginia*, a sister ship to the S. S. *California*.
3. The construction of a third 18,000-shp. turbine electric drive passenger vessel, S. S. *Pennsylvania*, a sister ship to the *Virginia* and the S. S. *California*.
4. The construction of two 14,600-shp. twin screw turbine electric drive vessels for the Ward Line.
5. The construction of a 12,600-shp. twin screw turbine electric drive vessel for the Grace Line.
6. The placing in service of three 4000-shp. single screw Diesel electric drive cargo ships: M. S. *Courageous*, M. S. *Triumph*, and M. S. *Defiance* by the U. S. Shipping Board.
7. Several smaller craft utilizing Diesel electric drive.

The results of the Jones-White Act are already being felt by the marine industry. A few large ships taking advantage of the provisions of this Act are in the course of construction and contracts for several large vessels are pending, most of which will probably employ turbine electric drive.

The use of electric auxiliary machinery is established, and in most cases the auxiliaries throughout the ship are driven electrically.

Applications to Mining Work

ANNUAL REPORT OF COMMITTEE ON APPLICATIONS TO MINING WORK*

To the Board of Directors:

In the past many criticisms have been made against the mining industry as being backward in modern developments. Certainly such criticisms are no longer justified to the same extent as a decade or two ago.

During the past year there have been many developments of electrical apparatus for mining work and the operators have not disregarded the applications offered. In fact, the operators have sought relief in every possible way to reduce operating costs. Overdevelopment during the war has not been absorbed by increased consumption of coal. This is largely due to rapid improvement in efficiency in large electric power plants, electrical interconnection, and in improved railroad performance.

Metal mines have been similarly affected from overdevelopment and lack of increased demands.

It is generally predicted that both coal and metal mining are entering a new era of development. Further mechanization is considered as a solution to the problem of cost reduction. Mechanization implies further electrical application to all types of mining equipment.

A few years ago there was considerable discussion on superpower systems. Without a great deal of publicity these superpower systems have developed until now practically every industrial and mining field is served from high-voltage interconnected lines receiving energy from large efficient power plants. Thus it is logical that the major part of the further electrification and mechanization of mines will be served from the electric utilities.

Hoists. Due to high cost of equipping shaft mines with electric hoists the change over from steam to electric is slow. One such change over a medium capacity mine is worthy of note, not for its size but for the rapid cycle. A 750-kw. synchronous motor-generator set supplies an 850-hp., 116-rev. per min. motor through Ward Leonard control.¹

The hoist operates in balance and is designed for 230 trips per hour from a depth of 282 ft., with a maximum rope speed of 3300 ft. per min. The cycle allows for 5 sec. acceleration, 1.65 sec. full-speed running, 5 sec. retardation, 4 sec. caging. Actual per-

formance of 258 trips per hour has been attained by reducing the caging or stop period to two sections.

The motor-generator set is remote controlled from the operator's platform. No auxiliary hoist motor is provided. The hoist is controlled through master controller and time limit relays for both acceleration and retardation.

In the mountain mines, a-c. motors have been applied for control and regenerative braking to control heavy descending loads previously handled by large drums and mechanical brakes. The power saving is appreciable and safety of control is valuable.

Fans. Synchronous motor drives for fans have been applied in sizes up to 500 hp.² Increased efficiency and improved power factor are accomplished.

Continued applications of automatic starters for fan motors have proved desirable to reduce to a minimum the delay in the restarting of fans after power interruption.

Motor-Generator Sets. Automatic substations for motor-generator sets have increased in number both to save in labor of attendance and to provide better service for supply of direct current to remote load centers.

Automatic power-factor control on synchronous motors has been accomplished on several sets.

Cleaning Plants. With the mechanical loading of coal being accomplished and with more discriminating buyers of coal, the industry has turned to mechanical cleaning. Several large bituminous coal cleaning plants were completed during the year.³ Thus, the soft coal industry is approaching the practise of the anthracite breakers. These wet washing plants use around 150 motors of various sizes, aggregating some 1200 hp. connected load. Texropes or V-shaped multiple belts, permit of standard motors in most applications to secure proper speed reduction in short space. Three such plants on one public utility service add a very desirable day load.

Shovels. In metal mining the 3-, 4-, and 5-yard electric shovels using shunt motors and Ward Leonard control continue to be installed to effect economies.

Additional 15-yard stripping shovels, weighing 1550 tons, and carrying motor-generator sets with 1500-hp. synchronous motors continue to be installed.⁴

Improved rubber covering for trailing cables has made these safer and more dependable. They usually carry 4000 volts, three-phase with a fourth wire for ground. Occasionally when blasting, these cables are damaged. Field vulcanizing has been perfected so that the outer covering is repaired so well that it will stand up through

2. Installed at Chicago, Wilmington, and Franklin New Orient mine, West Frankfort, Ill.

*COMMITTEE ON APPLICATIONS TO MINING WORK:

Carl Lee, Chairman.

A. R. Anderson,
F. N. Bosson,
Graham Bright,
M. M. Fowler,
E. J. Gealy,
L. C. Hsley,

G. M. Kennedy,
R. L. Kingsland,
A. B. Kiser,
W. H. Lesser,
John A. Malady,
C. H. Matthews,

F. O. Nicholson,
W. F. Schwedes,
F. L. Stone,
E. B. Wagner,
J. F. Wiggert,
O. D. Woodward.

1. Equipment furnished by General Electric Co. and installed at Peabody Coal Co., Mine 53, Springfield, Ill.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

water and oil the same as the original cable, thus saving a great deal on replacement costs.

Slushers. Metal mines have almost completely adopted motor-driven underground slusher machines to replace air driven machines.

Locomotives. One manufacturer has developed roller bearing application to motor support on axles to maintain the gears in exactly correct mesh.⁵ Experience in the field has not yet proved whether this will be acceptable practise.

Heavy service due either to large locomotives or very frequent travel of locomotives has led a number of mines to go to 6/0 trolley wire instead of 4/0.

Mining Machines. The manufacturers of mining machines have brought out improved track mounted cutters (Fig. 1). These can be built to cut at any height in the coal seam that is required. These machines consist essentially of a heavy frame mounted on trucks containing traction motor and a swinging section pivoted at the

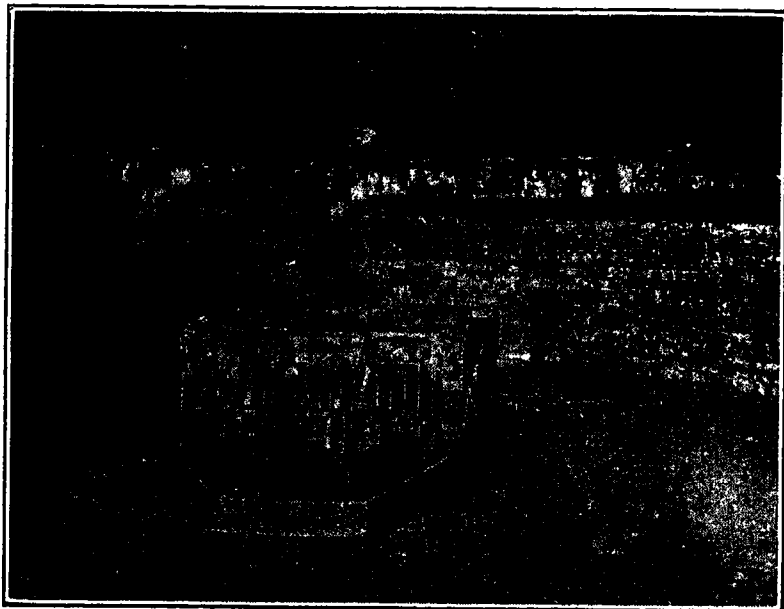


FIG. 1—TRACK MOUNTED BOTTOM CUTTER

front end of frame. This section carries the motor gearing, raising, lowering, and tilting mechanism, and the cutter bar and chain proper. The advantage of this type cutting machine over the breast machine and short-wall machine is that no unloading or loading of cutting machine proper is required. This feature eliminates most of the manual labor, and through higher power and saving of time enables the operator to practically double his productivity. One make of machine is equipped with a drill so that the same crew can drill for the blasting.⁶

In cutters for coal seams less than 30 in. high; it is difficult to place all controls convenient to the operator. One manufacturer has partially overcome this by applying contactor control to the machine. This control is of the "permissible" type construction, having

been worked out to meet the tests of the Bureau of Mines.⁵

A recently developed machine is the hitch cutter.⁷ This is a very special type drill to cut hitches in sides of rooms of coal mines to enable timbering to be carried to the face without interfering with cutting and loading machines. This should materially reduce accidents at the coal face.

Loading Machines. One type of loading machine usually called pit car loader has been extensively in-

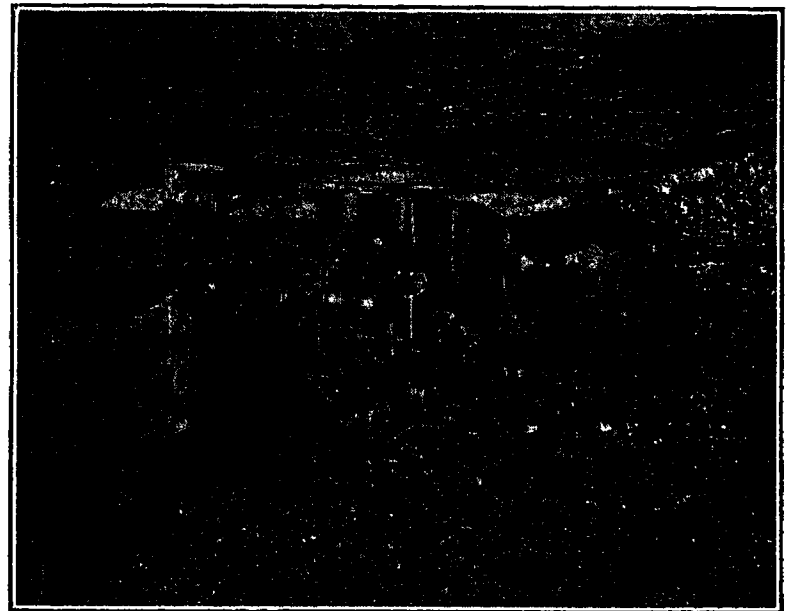


FIG. 2—PIT-CAR LOADER



FIG. 3—TANK TREAD LOADER

stalled (Fig. 2). Approximately 2000 have been placed in service. They consist of short drag type conveyor driven by $\frac{1}{2}$ - to $7\frac{1}{2}$ -hp. motor. In this machine coal is shoveled onto the loader which discharges into mine car.

Full mechanical loaders of several types have been improved and are coming into more general use (Fig. 3). These vary in design, using from one to eleven motors,

7. Goodman Manufacturing Co.

3. Pittsburgh Coal Co., Pittsburgh, Pa.

4. The United Electric Coal Co. at DuQuoin, Ill.

5. Jeffrey Manufacturing Co.

6. Sullivan Machinery Co.

having from 15 to over 100 connected horsepower. Reports indicate that approximately 3 per cent. of the soft coal mined in 1927 was loaded mechanically and most recent reports indicate over 22 per cent of coal mined in Illinois was loaded by mechanical and pit car loaders.

Blasting. Continued experiments in smokeless shooting of coal have been made.⁸ In this a gas is compressed to high pressure in the cartridge, then fired by means of fuse in heavy detonation or heating element. This fuse requires about 100 amperes at 180 volts to set off heating element.

Telephones. One company installed a complete system, using lead-covered pair in conduit laid in the floor of the mine.⁹ In rapid hoisting, the caging is limited to 1½ or 2 sec. This does not permit the check puller to safely detach the identification checks. Several mines overcame this by installing loud speaking telephones between top and bottom.¹⁰ The bottom man pulls the check and telephones the weighman giving him the number of the check.

8. Cardox.

9. Youngstown Sheet and Tube Co., Dehue, W. Va.

10. Peabody Coal Co., Mine No. 8, Tovey, Ill.

Switch Throw. An electrically operated switch throw has been successfully applied to mine switches.¹¹ This eliminates the danger of having these thrown by hand. Also signal lights are worked in conjunction with the throw.

Welding. Electric arc welding is becoming more common for repair work. It is almost universally used for welding rail bonds. This year has brought a new use in the welding of a very hard special metal to the tips of mining machine bits, to produce ten times the wear.¹²

Safety Work. The Bureau of Mines continues to test all types of equipment to be used in gaseous mines. They have now placed their stamp of approval on 30 various types of motors.

The approved cap lamp with greatly increased illumination is being rapidly adopted.¹³ Over 30,000 of this type have been placed in use. A new cap lamp with lead battery and dry electrolyte has been developed.¹⁴ This should reduce accidental burns from electrolyte.

11. Mines Equipment Co., St. Louis, Mo.

12. "Blackor."

13. Edison Models E. & F.

14. Concordia.

Power Generation

ANNUAL REPORT OF COMMITTEE ON POWER GENERATION*

To the Board of Directors:

An organization meeting, following selection of the committee membership, was held on November 2, 1928, in which the program of the previous year was reviewed and subcommittees appointed to undertake and initiate activities concerning the following subjects:

1. Excitation Systems and Auxiliary Drives in Electric Power Plants, Sub-Chairman, Mr. F. T. Leilich.
2. Interconnection, Sub-Chairman, Mr. F. C. Hanker.
3. Rehabilitation of Power Plants, Engineering and Economic Features, Sub-Chairman, Mr. C. F. Hirshfeld.
4. Hazards to Service Reliability in Modern Generating Stations, Sub-Chairman, Mr. E. B. Meyer.

A second meeting was held during the period of the Winter Convention. Reports at this time outlined the scope and progress of the plans undertaken by the subcommittees. The Subcommittee on Interconnection recommended that its problem was of sufficient magnitude to justify a symposium at one of the national conventions, and the committee decided accordingly to lay plans for a group of papers and accompanying discussion on some important phases of Interconnection during the Winter Convention in 1930.

On April 10, a meeting of representatives of the Excitation, Auxiliaries, and Interconnection Subcommittees was held in Pittsburgh, which members of the Electrical Apparatus Committee of the National Electric Light Association attended, for the purpose of discussing the scope of the investigations that have been or may be undertaken by the two committees in the interest of minimizing any duplication of work that might develop without coordinated efforts. The discussion brought out that no studies were planned by the N. E. L. A. committee on the subject of Excitation, but that the 1924 report of the N. E. L. A. on Auxiliary Drives was scheduled for revision during the next year. The data collected by the Subcommittee on Auxiliary Drives for the present report have accordingly been transmitted to the N. E. L. A. committee for their purpose. The program of investigation and study of the subject of Interconnection that has been outlined by the N. E. L. A. committee seemed so comprehensive that a considerable period would be required for its completion. The papers proposed for the A. I. E. E. sym-

posium, after discussion, appeared to lie entirely in one section of the N. E. L. A. outline, and it was decided therefore to proceed with their presentation and to consider them as one source of information and data for accomplishing the study outlined by the N. E. L. A. committee.

The Subcommittee on Excitation Systems and Auxiliary Drives has endeavored to summarize present day practise with regard to these important features of power-plant design and operation. Its report in detail follows, and leaves nothing unfinished for transmittal to next year's committee.

The Subcommittee on Interconnection has classified the problems which it recognizes in that subject into groups relating to technical, economic, and operating considerations. It has associated with its own membership affiliates from the several sections of the country in which interconnection experience is accumulating, and has designated certain of its personnel as liaison members to cooperate with committees of other appointment that may treat subjects related to Interconnection. The subcommittee has outlined a series of papers of valuable potentialities to the industry. Its report, which follows, is at this time mainly in the form of an outline of work which has been initiated, and constitutes the only subject matter which the committee wishes to transmit to its successor of next year.

The Subcommittee on Rehabilitation of Power Plants has viewed its subject from the angle of future development and possibilities, after depicting the economic and technical causes which are likely to bring about the desirability of rehabilitation, or modernization. The report of the subcommittee as prepared by Mr. C. F. Hirshfeld introduces so many valuable points of view that the committee has thought it better to present it for publication at the Summer Convention as a separate paper, rather than to incorporate it in this progress report. An Institute paper entitled *Increase in Generating Capacity of Existing Stations and Equipment on the System of the Columbia Gas and Electric Corporation*, by Mr. E. S. Fields, describing a well planned rehabilitation program with regard to the generating capacity in the vicinity of Cincinnati and Dayton, Ohio, was reviewed with interest by the subcommittee during the year, and proved such a fine example of a subject becoming increasingly important, that the subcommittee recommends it to the attention of all engaged in the economics of power station development. This paper is scheduled for publication at an early date.

As could be expected, the recent innovations in the practise of power generation have introduced new hazards and problems affecting the service reliability of generating plants. These have been pointed out and discussed in the report of the Subcommittee on Hazards

*COMMITTEE ON POWER GENERATION:

F. A. Allner, Chairman,

J. R. Baker,

A. E. Bettis,

J. B. Crane,

P. M. Downing,

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N. E. Funk,

W. S. Gorsuch,

F. C. Hanker,

C. F. Hirshfeld,

A. H. Hull,

A. H. Kehoe,

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G. L. Knight,

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Arthur R. Smith,

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R. W. Stovel,

W. M. White.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

to Service Reliability in Modern Generating Stations, which is appended in final form without recommendation of further study at this time.

The purpose and scope of the yearly progress report was defined at the first meeting by members of the Executive, Coordination of Activities, and Publication Committees of the Institute. It is obvious that a tabulation of present day power developments and trends would be a stale repetition of technical literature closely followed by those engineers directly concerned with power generation. However, of the Institute membership of 18,000 engineers there are many who are in no way associated with power generation activities; there is also a considerable body of electrical engineering students reading current Institute literature to whom a yearly summary or picture of the power generation industry should be presented; and another group, to whom the yearly progress reports should be of interest as well as value, includes the more recent engineering graduates who are in the process of orienting themselves in the engineering professions. Exposition of the progress, development, or trends in power generation is best made by reference to typical generating plants; but in pointing out the salient features of illustrative plants, an element of selection was necessary to avoid undue volume. However, bibliographic references are given in connection with plant descriptions, so that anyone interested in further detail of plant construction can readily locate it. For this reason the bibliography at the end of the report is not so comprehensive as that embodied in the 1927 progress report, but is confined principally to the technical papers or reports presented to or prepared by the various engineering societies on matters pertaining to power generation. If this report presents a picture of the new developments in the field of power generation, portrays in its subcommittee reports some of the economic and technical problems which the industry is facing, and offers a reflective summary of the lines along which this phase of electrical-mechanical engineering is expanding and advancing, it will have achieved its objectives.

RECENT DEVELOPMENTS AND PRESENT STATUS OF POWER GENERATION

Volume and Distribution of Generation

The volume of generation of electric energy has continued to increase in step with the general business situation throughout the country. Numerically, the output of all central generating plants in the United States in the past year has been almost exactly 10 per cent greater than in the preceding year. The industry as it approaches the half century mark saw an annual growth equal to its entire volume 20 years ago, while the generated output of 1928 was over 11 times that in 1908. It is only a matter of months now until the yearly production of central generating plants will have reached the figure of one hundred billion kw-hr.

A relative index of note to anyone contemplating this field of activity shows that the electric output has doubled in the last six years.

While the opinion seems to prevail that activity in undertaking new hydroelectric developments is lagging for one reason or another, the fact is prominent that hydro plants produced last year 40 per cent, or better, of the total output of central generating plants, which is a larger share of the total power generation than in any year of the last decade. This relatively high percentage of hydro output was in part due to better than average rainfall conditions.

Fuel burning plants generated practically all of the remaining 60 per cent of the year's output. Internal combustion engines continue to be used for power production, in certain localities where liquid and gaseous fuel supplies are economically available and the load demands are relatively small. Steam production by direct firing of oil and gas under boilers is the prevalent method in these territories when volume output of electric power is necessary. The relative proportion of coal compared to oil and gas fuels used for steam raising has remained constant for 10 years, coal constituting almost 90 per cent of the fuel burned.

The statistics available indicate that the volume of electric output in plants other than central generating stations is about 30 per cent of central station production. There can be no question, though, that the advances in the art and practise of power generation originate largely in the central station industry, and are later utilized by the general industry of the country as specific conditions may warrant; also that the relative use of central station power in industry has increased in the last 10 years from less than one-third to almost one-half of the power requirements of the country's industry.

Generating Plant Building Programs

The past year was notable with respect to the quantity and character of generating capacity placed in initial service. The year 1928 was a peak year for the number of new hydroelectric stations and for total capacity installed, exceeding 1927 by over 100 per cent. It is probable that 1929 and 1930 will see the addition of new hydroelectric generating facilities at about the same rate as in 1927. With few exceptions, the hydroelectric units were installed in new developments and constituted only a portion of the expected ultimate generating capacity. More novel features of hydroelectric practise, to be discussed more fully later, were exemplified in the 1928 additions than in any other recent year.

In contrast with the 1928 hydroelectric installations, there were only one or two new steam-electric plants placed in initial operation that are noteworthy for any outstanding features, and only four or five steam plants of major considerations will be started up in 1929 or 1930. Practically all the increase in steam-electric generating capacity, exceeding the new hydroelectric

capacity by about 75 per cent, was added to existing plants. The size of units is the only striking characteristic of the 1928 steam additions.

The relative paucity of new steam plants in the past year probably is an outcome of the wide recognition a few years ago of the impending rapid growth of power generation, and the simultaneous provision through the country of a backbone of highly efficient steam stations strategically located to carry the load arising in ensuing years. The data for 1928 show that practically the entire growth of steam generated load was taken by extensions to existing plants, but it is also evident that many of these stations are approaching the limit of their development, and consequently a wave of new steam stations may be expected in the next few years.

It is probably correct to say that the past year witnessed opposite phases of the recurring cycles of hydro and steam developments. The growth of system load, both from increasing density and from interconnection or joining of small components, has made the use of larger and larger generating plants economically feasible and requisite. Generating capacity must be ready when needed and the starting of a new station in the absence of the possibility of extending existing stations is therefore imperative, often several years in advance of the time when the ultimate development will be required. This situation is met by plans calling either for hydro or steam generation, provided, of course, that water power sites are available within economical distance of transmission. A hiatus of several years then occurs, depending upon the rapidity of load growth on any particular system between the starting of new generating plants. The interval is consumed in enlarging the last station to its full, economical size.

Economics of Hydroelectric Developments

There has been much comment recently about the slackening in hydroelectric development in the United States, although the hydroelectric industry is flourishing in the neighboring country of Canada. Various reasons are advanced for the situation in this country, chief among which are the average high fuel efficiency, the lowered cost of fuels, and the reduced investment cost of steam-electric stations. Another fundamental reason may be that practically all of the low cost water-power sites in this country have been developed, while the more costly sites adjacent to the market and the low cost sites that are now remote from load centers, require development on a large scale to make them economically feasible, as minor utilization of the sites would throw too great a burden of fixed costs upon the hydro energy generated. This economic limitation is probably the controlling factor in determining the cycle, or fluctuation, of water-power developments. It seems likely that the next few years will be a period in which existing hydroelectric plants will be extended to their ultimate size, and during which the growth of load will finally

culminate in an impetus leading to hydro development again on a major scale. In the meantime, load increases will be assumed by extensions to, or construction of, steam-electric plants whose capital cost can be estimated with considerable assurance, and incurred in relatively small steps as necessary.

There is a growing realization that wherever a feasible development of hydroelectric power is possible, the combination of hydro with steam generation on the modern utility system leads to the lowest over-all cost of power generation. It is becoming apparent that hydro power has more than an energy and minimum flow capacity value on systems mainly steam, and on systems largely hydro, the advantage of steam-capacity steps to defer major hydro undertakings until economical is being recognized. The value of even limited hydro energy for peak service is receiving wider appreciation, and in many other respects, the interrelation of the two sources of power is being fully worked out. Such considerations together with the attractive over-all generating costs of efficient steam stations have led to the adoption of extensive modern steam plant facilities in regions dependent in the past on water power.

Comparison of Plant Efficiencies

The efficiency of the utilization of water-power is probably approaching its attainable limit as in the past year there was corroboration of peak efficiencies of the order of 92 to 94 per cent based on net effective head, in small as well as large capacities, and for a range of heads to which the Francis type of turbine is applied. The propeller type turbine is reaching efficiencies of 87 to 90 per cent, while the impulse wheel which is used for the high heads in the West has shown efficiencies in recent installations better than 85 per cent over a broad range. Hydro plant water efficiency depends principally on one mechanical element, and the cost of this machinery is usually not over 10 to 15 per cent of the capital value of the entire development. The cost of the maximum attainable efficiency is therefore rather a minor item in the whole. Steam plant efficiency occupies just the opposite side of the picture, as it is the result of the combination of four separate efficiencies, those of the turbine, the boilers, the auxiliary arrangement, and the working cycle. The capital cost of the machinery components of these varies at the present time between 50 and 55 per cent of the total station cost, and the cost of any extensive effort to build in the ultimate of efficiency has a definite effect upon the total. Nevertheless it has been found economically possible to attain steam turbine efficiencies of 80 to 84 per cent, boiler efficiencies of 85 to 90 per cent, and to select a working cycle and machinery arrangement that will result in an overall plant efficiency of 23 to 27 per cent.

Major Influences in Station Design

The two agencies that were of major influence in the design of the stations that were started or extended

in the past year have been the expansion of system loads, and the possibility of high station efficiency with decrease of over-all cost. Greatly increased system loads have resulted from normal growth as well as from interconnection between small or isolated systems, and in many cases between systems of metropolitan size. Hydro developments have probably been more stimulated by interconnection of systems than have steam plants, which in the majority of cases are built as close to the load as possible. As a rule hydro plants, even though water efficiency has increased two to three points in the period, have not had the opportunity of raising their internal efficiency with a corresponding reduction in over-all costs that has been open to steam plant design. The size of system load has led to larger and larger generating units, both in hydro and steam plants, and the increase in size has permitted a slight betterment of internal efficiency; the much greater benefit, however, comes from concentrating capacity in a few large units rather than in numerous small machines. The building volume of turbine and boiler rooms per kilowatt of capacity has been reduced 24 to 41 per cent in recent additions to well-known stations where the newer units are appreciably larger than the turbines in the initial sections of the plants. The adoption of improved working cycles and better combustion facilities in the steam plants has been chiefly responsible for a 9 to 10 per cent decrease within the last two years in the average pounds of coal per kw-hr. produced, the average coal rate at the end of 1928 being about 1.76 lb.

The best thought of hydro designers is being applied to the reduction of the investment charges and extends from the study of preliminary costs to an evaluation of the capital savings that might be secured by a diversity of construction and loads on interconnected systems of wide scope. In many instances great concern centers around the development of maximum output of secondary power, both by the use of a machinery installation that is large compared to the minimum steady output, and by the maintenance of output under unfavorable hydraulic conditions. The first scheme requires a system load capable of absorbing the secondary power in high water periods and protected by available generating capacity during low water; the second scheme depends upon the adaptability of the hydraulic design to fluctuating water stages. The feasibility of the second largest hydro plant started in operation in 1928, that on the Ohio Falls at Louisville, was greatly enhanced by a turbine design that permitted an attractive output under a wide range of heads. The interconnection of steam and hydro has given rise to another possibility of increasing the hydro output, but in this case for peak purposes in low water periods. The year 1928 saw the first large pumped storage development in this country started on the Rocky River in Connecticut, where pumping facilities have been provided to supplement the natural storage accumulated during the high

water season. Locations for watershed reservoirs are being sought and will be utilized to their economic limit for the conservation of flood flows, the increase of steady or primary power, and the lessening of property damage and unfavorable hydraulic operating conditions during normal high flow periods. The use of large units has been accompanied by an improvement in the detailed design of turbine, generator, and waterways, so that the cost per kilowatt of rated capacity has been materially decreased. An interesting step further toward lowered capital costs was the omission of the generator room superstructure at the Norwood plant in North Carolina that was brought into service within the past year. While this is not the first application of the idea, the generators at the Norwood plant are the largest to date arranged only with individual canopy coverings. Another method of capital cost elimination that is being given scrutiny is the simplification of the generator voltage bus layout and station service supply; the outdoor arrangement of high-tension apparatus has manifested its superiority from a cost point of view for several years.

Steam plant designers have been busy discussing the application of extremely high steam pressures and calling attention to the possibilities of higher steam temperatures; the selection of the most suitable method of combustion has also been a major concern. In many instances the necessity for maximum capacity has been a determining influence in the station design and it is not at all uncommon to find two methods of combustion employed in the same station, as well as two working pressures. Designers are evidently giving a great deal of consideration to making best use of the various ideas of plant design and arrangement that have been tried out successfully in practise. Several years ago the regenerative and reheating cycles were introduced and are now in general use. It is quite probable that the next major step is toward the use of extremely high pressure superposed upon a pressure now standard. However, the record thermal economy to date is held by a medium high-pressure station that carries its steam pressure only up to 650 lb. The advocates of super-pressure state that the capital cost of such a station is no higher than of a standard pressure plant when allowance is made for all factors, particularly that of capacity. The same argument is heard for the pulverized fuel plant. Both high pressure and pulverized fuel are supposed to show somewhat higher efficiencies at the maximum capacities claimed for them. In the end the arguments generally resolve themselves into the question of capacity per dollar, or a reduction of the investment per kilowatt. The relation of the investment charges to the fuel and operating costs does not appear to change to any extent for as the first is decreased by the concentration of capacity, the other has been falling because of the betterment of efficiency. It cannot be said that steam plants are becoming any simpler in their design layout; just the opposite. As

the regenerative cycle introduced additional equipment into the turbine hall, so the new combustion methods and heating surface arrangements add complexity to the boiler plant. Station auxiliaries have multiplied and brought with them a host of control apparatus, and it is being recognized that perhaps the cost of this sub-auxiliary equipment is becoming excessive. The justification for all the complexity is found in the higher efficiency, and this with the greater capacities have kept the over-all dollar costs satisfactory from past points of view. Some simplification is appearing in particular instances and more can be expected, with a consequent lowering of investment costs. It is well to bear in mind, however, that when the changing purchasing power of the dollar, and the effect of interconnection of reducing the amount of station inherent spare capacity, are considered, it may be probable that the absolute cost of steam plants has increased.

To date, the savings available by building new steam plants embodying modern cycles and heat reclaiming devices usually have been so marked in comparison to enlarging and continuing for heavy generation older stations of lower thermal economy, that the system growth has been accommodated on new base load plants and the older stations have been relegated to peak load service. Engineers are beginning to question the amount of improvement in operating economy that is still possible, and are looking for other ways to increase capacity at low cost and without sacrificing their present stations to a low use factor in coming years. Where peak loads cannot be avoided either through interconnection diversity or off-peak load development, serious consideration is being given to the design of plants for peak purposes only that would have a low capital cost although possibly a higher operating cost than their companion base load plants. The general idea of such a plant is a few large units of varying capacity with only the simplest of auxiliaries and heat savings devices, although European variations of the plan include a heat accumulator for storage of energy during off-peak hours for use later on the peak and Diesel engines of capacities as great as 15,000 hp. In this country the alternate pumping and release of water between artificial or natural reservoirs is being given more study by steam system operators than the proposal of off-peak heat storage.

Rehabilitation of Existing Steam Plants

A main line, however, along which the efforts of steam station designers will be increasingly directed, points to the rehabilitation or partial revamping of the efficient stations now in use. There are instances now at hand where it has been possible to step up materially the station capacity at a price per kilowatt about half the original cost; and this has been found warranted and feasible in plants of rather recent design. One way of accomplishing this is to compound a higher pressure station element upon a low-pressure plant, and pressures

of 700 and 1200 lb. have been thus added to existing 185 and 300-400-lb. plants. Another method consists of adding a turbine element receiving steam at the standard or normal pressure, in cross-compound arrangement to an existing turbine element, the original turbine being altered or the intermediate pressure so selected that the original capacity can be maintained and the capacity of the new element added as net gain. The same idea has been applied to the combination into a single unit of two separate and adjacent turbines by placing between them an added turbine element that exhausts into the low-pressure elements of the two separate machines. In plants where the boilers are only a few years old, they are likely to be of such size that their operation imposes no excessive labor and maintenance costs, and the problem of increasing the boiler output hinges usually upon fuel burning limitations. The development of water and steam cooled walls has removed the hazard of refractory deterioration that existed previously, so that greater fuel feeding and combustion facilities are the principal requirements for increased capacities. That these are available either for solid or pulverized coals has allowed major increases in boiler plant outputs. Older boilers that are usually of small size and of low working pressure generally do not allow of any rearrangement of settings that is worth while, and the problem is nearly always settled in such cases by replacement of individual boilers or the construction of an entirely new boiler plant.

Rehabilitation of Hydro Developments

Rehabilitation or revamping in hydroelectric design is nearly always more inconveniently carried out than in the case of steam plants. In some cases the hydro plants have been almost completely rebuilt in order to utilize the site head more efficiently; in other instances the dams have been raised to increase the effective head. The revamping of hydro plants often requires interference with their output over extended periods with consequent economic loss. Where it may be desirable and possible to raise the operating head it may be found that the dam will not withstand the increased static pressure, and practical reconstruction of the dam must be undertaken to utilize the entire site head.

There appear to be at least five types of hydro developments that offer the possibility of revamping as soon as it is economically feasible, as follows:

1. Localities where the flow is divided among several small and inefficient units, either in one plant or among several plants in the same area.
2. Situations where considerable overdevelopment of the minimum flow would be advantageous with respect to system interconnections, but where the available waterways are at present obstructed by small capacity, inefficient units.
3. Plants where the site losses are excessive and the available head could be better utilized by modern waterway construction and settings.

4. Plants where the possible head was not fully developed initially.

5. Plants of partial development and insufficient flow capacity interposed between more modern plants on the same stream in such locations that the river flow cannot be ponded most advantageously.

Methods of Reducing Operating Costs

The attack on the initial costs of generating plants is being paralleled by similar efforts towards a reduction of later operating costs. The operating results of plants are being scrutinized at frequent intervals and compared with operating standards that have been prepared from tests, operation under known conditions, and from manufacturers' guarantees or expected performance data. These studies may be in terms of direct cost for such items as labor, supplies, and maintenance, but the greatest concern is given from the point of view of operating performance to strictly operating statistical figures such as thermal economy and water equivalents. The analysis frequently is modeled along the lines of an accounting balance sheet, and is termed a heat or water balance. Its essential purpose is to explain the deviation from standard performance. Two very informative serial reports on this subject were published during the past year by engineering committees of the National Electric Light Association on "Waterwheel Testing and Operating Records of Plant Discharge" and "Power Station Betterment." The interest in checking plant performance has led to an increased use of measuring devices of the totalizing type, particularly in steam plants. Attention is centered upon water discharge and leakage in hydro plants and there are numerous instances in the later hydro installations of converging sections of the intakes or penstocks being arranged for Venturi measurements. The differential heads available at various locations in the pressure waterways are also used for metering purposes. The Venturi sections and by pass devices are calibrated in place by accurate water measurement usually at the time the waterwheels are also being tested. The field testing of waterwheels is now considered requisite both for the purpose of checking guarantees as well as for securing performance data, and it is estimated that about 400 waterwheels have been thus tested within the last eight years.

The trend to larger boiler, turbine, and waterwheel units has reduced the number of operators required to man the modern power plants but recourse is being made in many instances to automatic control of machinery for further reduction of operating labor costs. Often the primary reason for adoption of automatic control is to secure a more constant improved efficiency, and sometimes reliability of operating processes is a desired object. The increased operating efficiency accrues from the mechanical performance of repetitive adjustments which would not be carried out so thor-

oughly by manual control unless considerable excess operating and supervisory labor were employed. In steam plants, the chief use of automatic control is for the regulation of the combustion process, although in some plants the balance between the auxiliary exhaust steam and the feedwater heating is automatically controlled. Automatic control has received a great deal of prominence in connection with hydro plants in the last year, although the control feature has not been fully automatic in some cases mentioned as plants with complete automatic control. Saving of operating labor is the principal object in the hydro plants that are started and stopped by remote control, such as from a distant point or by forebay water level. Automatic synchronizing has been used in some plants in which operators are employed and the arrangement of equipment for the purpose has led to lowering of the initial costs of the control apparatus, an increased operating reliability, and a saving in operating labor. Control equipment is being devised so that it can be made fully automatic or remotely supervised as the circumstances may demand. There is a trend in steam plant design also to group the control apparatus so that more of the plant can be brought under remote supervision and control. In line with this the floor levels, machinery layouts, and wall construction are being adapted to the minimum operating force for the purpose of securing a higher grade of operating supervision at a lower total cost. The automatic regulation of frequency is being actively developed and its application in hydro plants is somewhat more preferred on some systems than in steam stations. It is expected that the control will be extended to the proper division of load between units in the same plant for the purpose of maintaining the highest possible hydraulic efficiency. Frequency regulation has as its object an improvement of system service, and the decrease of operating costs resulting therefrom is problematical at the present time.

ILLUSTRATIVE EXAMPLES OF RECENT HYDROELECTRIC DEVELOPMENTS

Large Run of River Plants

Conowingo. The Conowingo plant on the Susquehanna River may be considered typical of present day medium head, hydroelectric developments, in this case about 89 ft. It is essentially a run of river plant, the $2\frac{1}{2}$ billion cu. ft. of water available in the reservoir above the dam with a 7-ft. draw-down being less than the power house draught at full load for 24 hr. The hydraulic features, the machinery equipment, and transmission facilities have been thoroughly described in the A. I. E. E. Quarterly TRANS., Vol. 47, April and July 1928. Conowingo is outstanding in being now the second largest hydroelectric plant in the United States, and when extended to its final size will be the largest single hydroelectric installation in the country. Other features of bigness distinguishing it are the turbines that are the largest in physical size installed to date,

and the butterfly valves placed at the inlet of the scroll case for blocking the water passage during shutdown. These valves are the largest ever built, and in use show negligible leakage.

The hydro developments on the Susquehanna River well illustrate the growth of the electric power industry that has made possible the increasing machinery capacity that may be economically installed on any stream. The York Haven plant 43 mi. upstream, the earliest development, uses a flow of about 15,000 cu. ft. per sec.; the Holtwood plant, intermediate between York Haven and Conowingo, a flow of 31,500 cu. ft. per sec.; while Conowingo, with a maximum discharge of about 6500 cu. ft. per sec. per single unit, will utilize a flow eventually of 70,000 cu. ft. per sec. or more. Minimum daily flow as low as 3200 cu. ft. per sec. have been recorded at Holtwood. The median flow (available 50 per cent of time) is about 25,000 cu. ft. per sec. while flood flows may approach 700,000 cu. ft. per sec. Conowingo was feasible when the system load became of sufficient size to permit the plant to operate on base load at full capacity during the high water season, and to operate as a peak load plant at high capacity during low water stages. With a 24-hr. firm power value of only 30,000 kw., the plant can still be relied on during the period of expectation of the annual peak load for its full capacity of 252,000 kw., when used to carry the top portion of the present combined daily load curve of the Philadelphia Electric Company System and the interconnected companies; and in the course of a year it can be expected initially to deliver in Philadelphia 1,250,000,000 kw-hr., or almost five times its firm power value for 8760 hr.

The station structure and machinery layout at Conowingo show the modern tendency to incorporate the facilities for power generation in the dam structure with the view of securing the simplest and most compact arrangement possible. In fact about the only idea for simplification not embodied in the design of the power plant was that of the omission of a complete superstructure over generators, but the generator roof as erected is used to support an outdoor 220-kv. switching station with the result that the connections between generators, generator busses, step-up transformers located directly behind the head works in the dam structure, and the high-tension switch gear are minimized, and the switching station on the roof is readily accessible to the operating crew. The distance of 87 ft. from the face of the dam to the mouth of the scroll case is 11 ft. less than the depth of water on the upstream side of the plant. In this space provision is made for the generator bus galleries, the 26,666-kv-a., 220-kv. transformers with handling track below the highway mounted on the dam, and necessary control rooms and passages. No gate-house superstructure was erected, and the stop logs and trash racks will be handled by outdoor gantry cranes that also operate the crest gates on the dam.

The regulating and crest gates surmounting the dam spillway represent a method frequently used for providing for flood flows and of holding a maximum head in low flow periods. These gates are 38 ft. in clear span and 22½ ft. deep, although there are three gates only 10 ft. deep for regulation. All gates are of the Stoney or roller guide type. The piers holding the guides for the gates also support a highway bridge. The largest gates of this type in operation are on the dam of the Catawba plant in South Carolina, where steel gates 30 ft. high and 45 ft. in clear width are installed to pass flood flows.

The auxiliary and excitation systems at Conowingo reflect the latest ideas along the lines of reliability and operating convenience. Primarily the power for excitation and governor oil pumping is supplied to each unit by means of an individual shaft-end auxiliary generator of 500-kw. capacity mounted above the thrust bearing. This 440-volt a-c. generator has its own 250-volt exciter mounted above it. Other sources of auxiliary power are waterwheel driven station service generators and station service transformers. The excitation current for each unit is supplied by an individual motor-driven exciter set with pilot exciter, so that the problem of quick response excitation for stability purposes was readily met by a motor-generator speed of 1200 rev. per min. There is a spare motor-driven exciter set in addition to the individual motor-generator units. The governor oil pumping system is laid out according to the twin-pump arrangement, there being a complete pumping system for each pair of adjacent main units. Each twin group consists of two motor-driven pumps each capable of supplying the governors of both main units. This system lends itself to a simplified scheme of power supply and a minimum amount of extended station wiring, and provides adequate spare pump capacity so that there is little likelihood of interruption of the main units due to faults in the pumping system.

Louisville. The Louisville hydroelectric development that was brought into service during the past year is an outstanding example of a plant built for secondary power generation only, there being on the average 40 days in the year when power generation is impossible because of high water conditions. To meet this limitation the propeller-type turbine was installed so that power can be developed over a range of heads from 37 ft. maximum to 7½ ft. when the plant goes out of service. These machines at Louisville are the largest propeller-type wheels in physical size yet built in the United States and are approximately as large as any similar turbines in Canada or Europe. They can be started up, synchronized, and loaded at heads as low as 8 feet. The additional low head output secured by the propeller turbines gained at 10 per cent reduction in cost per kw-hr. as compared to a Francis type turbine installation. A further gain of 10 per cent also resulted from the higher wheel speed which allowed a direct saving in generator and building costs. The generators

in this plant employ the enclosed system of air circulation with water tube surface coolers, being the first installation of this type of generator cooling in hydroelectric stations. The unusual conditions surrounding the Louisville development have been discussed by H. G. Roby in November 1928 issue of *Mechanical Engineering*, Vol. 50, No. 11.

The abnormal hydraulic conditions during high river stages led to a quite unusual arrangement of the plant headworks. These will be entirely flooded over during high flow and the generator room, of 48 feet width, will be surrounded by water on three sides, making provision against flotation necessary. The headworks are of minimum volume and contribute little to the stability of the dam structure. The bulk or mass of the powerhouse section is directly under the generator room floor.

The Louisville plant was a pioneer in the adoption of supervisory control on a large scale in attended power plants. The entire electrical layout follows the unit principle. A 13,000-volt double generator bus is suspended in a steel enclosure along the upstream wall of the generator room, with the necessary switch connections for any generator below, on the generator floor opposite the particular unit. The generator switches are of the truck type. At each generator there is an individual control cabinet containing the instruments and relays for the automatic starting and stopping of the unit. Operation of the automatic control can be initiated by push button either at the unit control panel or at the central supervisory board. These control panels are placed close to the generator switches and minimize the conduit runs for switch operation. Connection between the unit panels and the supervisory panel is made by telephone cable. The circuits at the panels are completed by plug attachments, so that the control panels may be readily disconnected and interchanged if necessary. Miniature meters are used for indications on the unit and central panels. The turbine governors may be controlled by usual means from either location. This system of electrical control and bus arrangement, while introduced at Louisville to achieve minimum initial and operating cost under the peculiar requirements there, will likely be used in other stations, as evidenced by a comparable semi-supervisory control in one of the latest of high-pressure steam stations.

Dnieprostroy Project. An order has recently been received in this country for four Francis type turbines that will each develop over 100,000 hp. under a head of 123 ft. These turbines are being installed at Alexandrovsk on the Dnieper River in Russia. Each unit is rated at 84,000 hp. under a gross head of 116.5 ft. and at 88.2 rev. per min. The runners have a maximum diameter of 240 in., and weigh 300,000 lb. each. The runner shafts are 41 in. in diameter and weigh 160,000 lb. each. Power will be generated at 13,800 volts, three-phase, and 50 cycles. The outside diameter of the stator frames is 42 ft. The transmission voltage

leaving the power house will be 220,000 and 110,000 volts.

River Regulating Developments

Rocky River. The Rocky River pumped storage development for regulating the flow of the Housatonic River in Connecticut has been a major innovation in hydroelectric practise in this country during the past year. The technical features of this plant have been described in detail by E. J. Amberg¹ and mention of the plant is made here only for the purpose of making complete the review of the year's progress. The comparatively small natural run-off of the Rocky River, a tributary of the Housatonic River, is supplemented by water pumped from the Housatonic River into a storage reservoir created on the flow line of the Rocky River. Pumping is done mainly by off-peak steam power, and the direct recovery of the electric energy is carried out at an over-all efficiency of 61 per cent. However, this is raised to 79 per cent by the presence of another hydroelectric plant on the Housatonic River below the Rocky River station. The machinery equipment in the plant includes at the present time one vertical shaft 33,000-hp. turbine, and two vertical shaft 8100-hp. centrifugal pumps. The pumps discharge into the turbine penstock against a maximum head of 240 ft., and are the largest in this country, having a delivery each of 250 cu. ft. per sec.

Before the construction of the Rocky River storage reservoir the hydroelectric plants on the Housatonic River had only a primary or year round dependable capacity of 1000 to 3000 kw., although their installed capacity totals 26,000 kw. If the available hydro capacity was used on the upper half of the annual load duration curves, a firm capacity of 10,000 kw. could be secured. The regulation of the river by the Rocky River reservoir now allows a year round firm power of 11,000 kw. or if the firm power is used on the annual load curve, the total installed hydro capacity of 50,000 kw. can be counted on as firm capacity; in other words, the yearly firm capacity has been increased 40,000 kw. by the installation of a 24,000-kw. unit and by regulating the river flow with a pumped storage reservoir. This yearly peak capacity will increase as the load grows.

The drainage areas and storage capacity of this development are of interest for comparison with storage developments mentioned later. The drainage area of the Housatonic River at the plant farthest downstream is 1510 sq. mi.; the area of the Rocky River basin is 40 sq. mi, of which $8\frac{1}{3}$ are covered by the storage lake; 5.9 billion cu. ft. of water will be available from the reservoir although the natural inflow will be only 1.5 billion in the average year. In an average year the Rocky River plant will be called upon to generate 17,400,000 kw-hr. by drawing 4.03 billion cu. ft. from the reservoir; this water will generate 4,900,000 kw-hr.

1. A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1100.

at a hydro plant on the Housatonic River below the Rocky River plant.

Saluda River. In contrast to the Rocky River pumped storage reservoir is the monumental hydro-electric development now being carried out on the Saluda River in South Carolina. The natural flow of this river varies between 142 and 100,000 cu. ft. per sec. An earth dam almost a mile and a half in length and over 200 ft. in height is being thrown across the river valley to construct an impounding reservoir of 96 billion cu. ft. It is expected that the flood flow of the river will be reduced by 40 per cent, in addition to the regulation effected for power purposes, whereby some 300,000,000 kw-hr. will be produced annually. This artificial storage reservoir will rank in volume with other notable reservoirs, such as those at Gouin on the St. Maurice River in Canada of 180 billion cu. ft., the Elephant Butte in New Mexico of 115 billion cu. ft., and the Bitobi on the Gatineau River, Canada, of 95 billion cu. ft. The Saluda development is unique, however, in that the power house is situated directly adjacent to the storage control dam instead of being at a considerable distance from it, as is generally the case in the larger storage possibilities. The available drawdown of the reservoir will be 60 ft. At 180-ft. head the power-house discharge will be about 12,500 cu. ft. per sec. for the four 55,650-hp. units now being installed; provision is being made for two additional units.

Gatineau River Development. The recent inauguration of the Pagan Falls plant directs attention to a type of hydro development that is typical in some parts of Canada, where the topography includes concentrated drops suitable for power generation, and numerous lake basins scattered over the drainage area that lend themselves to storage control at relatively small cost. The territory covered by such reservoirs is usually remote and sparsely settled so that its inundation does not cause great damage to property. The most extensive of these developments has been on the St. Maurice River, where 4800 sq. mi. of the 16,200 sq. mi. of total drainage area are tributary to the Gouin and Manouan Reservoirs that are situated 230 mi. upstream from the Grand Mère, Shawinigan Falls, and La Gabelle Power Houses. The Gatineau River has been the most recent river in Canada to be largely developed; the erection of the Farmers Rapids, Chelsea, and Pagan, Power Houses near its mouth was carried out in conjunction with the damming of the Bitobi Reservoir about 120 mi. above the plants, where 95 billion cu. ft. are impounded. Further storage of 45 billion cu. ft. is also being built elsewhere on the river. The three plants have an initial installed capacity of slightly under 500,000 hp. The Pagan Plant is at the generating end of a 230-mi. transmission line to the terminal station in Toronto of the Hydro-Electric Power Commission of Ontario. This is the first 220-kv. system in Canada, and is noteworthy for the layout of the high-voltage switching installations at both ends

where all breakers are arranged in a ring with the equipment and lines connected to the ring between breakers. The scheme gives nearly the same flexibility as a double bus and materially reduces the number of breakers required, thus effecting a saving in capital cost.

Outdoor Type Plants

Norwood. The Norwood plant in North Carolina placed in operation in 1928 marked the peak development to date of simplification of plant superstructure, when two 22,000-kw. and one 18,000-kw. generators were placed under individual removable plate steel housings and arranged to be served by an outdoor gantry crane. While the idea is 12 to 15 years old, it has been adopted heretofore only for relatively small units. A modification that has been used in other plants is that of a low superstructure with a hatchway in the roof above the generator through which generator and turbine parts can be handled by outdoor crane. In some instances a low roof has been devised so that it could be rolled to one side as a whole, or in sections. In one instance an indoor gantry crane was installed to save crane runway beams and extra column steel. At Norwood the generators are enclosed in plate steel casings 40 ft. in diameter and 30 ft. high, with a horizontal joint between the cover plate and the cylindrical side plate. The gantry crane has unequal legs, one end of the bridge running directly on the top of the forebay wall, while the downstream leg rests on the concrete substructure enclosing the scroll cases. The crane trolley has an auxiliary drum operating a stiff leg derrick mounted at the upstream end of the crane bridge. This stiff leg derrick can be used for dismantling intake gates and screw stem gate hoists.

The division of total station capacity in the Norwood plant between two 31,000-hp. units (ultimately three) and one 25,600-hp. turbine for the improvement of plant efficiency is perhaps novel in large hydro projects. By the use of a single lower specific speed unit, high part-gate efficiencies are obtained when necessary because of the particular variations in stream flow and load conditions at the plant.

Another interesting and pioneer method for maintaining the most economical plant operating efficiency consists of an automatic arrangement for holding the proper distribution of load between units in the plant. It is recognized by hydro plant operators that most economical distribution of load cannot be maintained under swinging loads unless the switchboard operator is constantly adjusting the gate openings of the various turbines in the plant. With units of large size, the integrated deviations from the most economical loading in the course of a day may be appreciable and have led to the development of an automatic switchboard control that holds a predetermined distribution of load on the turbines by manipulation of the governor speed motors while allowing the governors to function in a normal manner for speed regulation. The load may be

automatically distributed between units of different size or characteristics, and even between stations.

Propeller Type Plants

The increasing use of the propeller type turbine has led to two mechanical modifications of it whereby the turbine power and efficiency can be maintained under decreased heads and fractional gate openings respectively. This is accomplished by changing the pitch of the propeller blades, either by hand after shutting down the turbine, or by a mechanical arrangement while the turbine is in operation. Six 5000-hp. wheels were placed in operation during the past year in the Chippewa Falls plant in Wisconsin, where the blade angles will be manually adjusted to give maximum efficiency for any gate opening or maximum output for any variation of head, according to load and water conditions. The normal head will be 29.6 ft. and each unit will pass 1750 cu. ft. per sec., running at a speed of $138\frac{1}{2}$ rev. per min. The peak efficiency is expected to be above $87\frac{1}{2}$ per cent.

Wheels of the greatest power of the manually adjusted propeller type, however, are being installed now in the Back River Plant of the Montreal Island Power Company in Canada, where six units rated at 8800-hp. under a head of 26 ft. and at 85.7 rev. per min. will be used.

The type of turbine having an automatic arrangement for varying the pitch of the runner blades is an entirely new development in this country, there being only one wheel so far installed. This turbine wheel has been used extensively in Europe where it is known as the Kaplan turbine. It contains a mechanism by which the governor changes the pitch of the blades while the turbine is in operation. Its chief advantage is the high efficiency that can be maintained over a wide range of gate openings. The 1900-hp. wheel being installed in the Devils River plant in Texas will operate at 277 rev. per min. under a head of 33 ft., and is expected to have an efficiency above 80 per cent for three-quarters of its load range, and above 90 per cent for the middle quarter of its range. Its efficiency-capacity curve is particularly flat compared to such curves for the fixed blade propeller and Francis wheels.

High Head Impulse Plants

Bucks Creek. The past year witnessed two record breaking impulse turbine installations on the Pacific Coast. The Bucks Creek Plant on the Feather River in California develops to date the highest head at any hydro plant in America, its static head being 2562 ft. This plant is noteworthy again from the point of view of waterpower practise in the East in that the stream draining one watershed is led into the flow line of a stream in an adjoining basin by means of a closed conduit 8 mi. in length; the combined run-off of the two areas is then carried by a tunnel through a mountain ridge into a stream on a third watershed, this stream being eventually diverted through a second tunnel

into the penstocks leading to the power house. Reservoirs located on the several streams receive three-quarters of the run-off of the entire area, so that a high degree of run-off regulation is secured. This plan of combining the run-offs of adjoining water sheds is feasible because of the very high power capacity of each cubic foot of water utilized at the tremendous heads that are available in the mountainous regions of the West, a fact which can be realized by consideration of the 300 cu. ft. per sec. flow provided to operate the two 35,000-hp. turbines in the plant.

Big Creek 2A. The addition to the Big Creek 2A plant of the Southern California Edison Company brought into service during the past year, contains the two impulse wheel units of highest capacity in the world, that are rated at 56,000 hp. each. The first part of this plant contains four units of a total rating of 82,000 kw., while the second section of the plant has a capacity of 95,000 kw. in two units. The floor space occupied by the new units is one-third smaller than that of the initial half of the plant, although it is likely that the second section of the plant would have been somewhat larger had it been erected remote from any other development. A further reduction in building volume amounting to a decrease in height of 39 ft. was secured by locating the 220-kv. transformers and oil circuit breakers outside of the generator room building. As in the case of the Conowingo units which feed into a 220-kv. transmission system, quick-response or high-speed excitation was desired for the Big Creek 2A units, and was likewise obtained by the use of a pilot exciter for the main exciter. However, the main exciter of 375-kw. rating, together with the 4-kw. pilot exciter, are coupled directly to one end of the main unit shaft where they run at its speed of 250 rev. per min., which is approximately three times that of the Conowingo generators.

Series Head Plants

The past year saw several new hydroelectric projects intended to utilize the undeveloped or partially developed head below existing plants in such a manner that the new plant operates in "water synchronism" with the plant farther upstream, there being no pondage between the two plants. The lower plant constitutes in effect only an extension of the upper plant, although they may be separated by several miles on the flow line of the stream, and is often remotely-controlled from the upper plant. An illustration is the plant at Lock and Dam No. 7 of the Kentucky River, notable also for its arrangement on "stilts." The width of the river at this point was too narrow to pass flood flows if a portion of the dam spillway were occupied by a continuous power house, and the plant was therefore erected on piers above the spillway. The forebay of the plant extends about four miles upstream to the outlet of the Dix River power house, the discharge of which will bring the Lock No. 7 plant into operation by water

level float control, so that the lower plant may be considered a head extension rather than a flow extension of the upper plant. The head at the Lock No. 7 plant will be 15 ft. The outdoor gantry type crane had a unique application here, also, in its cantilever extensions to handle water-borne material into and out of the plant, as rail facilities were not possible.

Another similar series-head installation was put in operation at the Chippewa Falls plant in Wisconsin, located only two miles below a plant erected earlier at Wisconsin.

Automatic Frequency Control in Hydro Plants

Hydroelectric plants seem to be taking the lead in the development of automatic frequency control, which is becoming more important as the smaller operating systems are being grouped into the large regional systems now in existence. Positive and fine control of the frequency, both instantaneously and accumulatively, appears to be a prime essential in all the problems arising in system operation. Two types of apparatus have been developed for frequency control, although both operate through the agency of the turbine speed motor and turbine control gates or valves. It appears to be possible to hold the frequency variation under two-tenths of one per cent on large interconnected systems. Regulation of the frequency on the New England Power System has been carried out at the Harriman Hydro Station on the Deerfield River, where three 15,000-kw. units are installed. Automatic frequency control is also in use at the Wallenpaupack plant of the Pennsylvania Power & Light Company where two 28,500-hp. wheels are installed. The first of these plants operates under a head of 360 ft. and at a waterwheel speed of 360 rev. per min.; the turbines in the latter plant run at 300 rev. per min. under a head of 300 ft.

The maintenance of exact frequency by one plant on a large system is somewhat contrary to the most economical loading of the units in the plant. The alternative of dividing the load fluctuations between a number of plants simultaneously appears to require too many complications at the present time. There seems to be a preference for the use of hydro stations instead of steam stations for the control of frequency, for the reason that it is easier to control mechanically the operation of the hydro unit than it is to vary frequently the steaming rate of the boiler plant. It is probable that the frequent movement of the hydro-wheel gates and servo-motor mechanism will cause increased wear of these parts which will be an expense chargeable to the automatic frequency control, but to date, this element of operating cost has not been evaluated.

Hydro Development Rehabilitation

The Bellows Falls development on the Connecticut River in Vermont is an example of the earlier New England canal layout for industrial purposes in which 75 small waterwheels utilized the available flow at

partial heads and low efficiency. They have been superseded in the new plant by three vertical units of 20,000 hp. each operating under a 60-ft. head. The project also covered increasing the height of the old dam, and providing greater spillway and canal capacity. A point of interest also is the two large rolling gates installed on the dam for crest regulation, which are each 18 ft. high and 115 ft. long.

The Catawba plant in South Carolina has replaced one built 23 yr. earlier having a capacity of 5600 kw. in eight rope-driven generators, operating at a best efficiency of 70 per cent. Originally the head was 23 ft., and the pond allowed only run of river operation. Raising the dam gave a 70-ft. head and created a 10-billion cu. ft. reservoir, and in conjunction with other storage allowed the installation of 60,000-kw. generating capacity in four units. At the Upper Tallassee plant on the Tallapoosa River in Alabama, a former 30½-ft. dam is being raised to a height of 56 ft. and two 24,000-hp. units are being installed. It was necessary at both the Catawba and Upper Tallassee plants to scrap entirely the former generating plants and dams.

HIGH-PRESSURE STEAM DEVELOPMENTS

Evolution of Equipment Types

The wider use of steam at 1200 to 1400 lb. seems to be the most conspicuous trend during the past year or so in the steam-electric generating field. The turbines used at these pressures have been satisfactory adaptations of previous turbine design. The initial installations were made in existing stations as superposed pressure additions, allowing the high-pressure turbines to operate on base load generation, so that single valve turbine control was sufficient. Lately multivalve turbines have been designed for plants where they will carry a varying load, making a uniform turbine economy desirable. Both impulse and reaction type turbines are used, although the reaction turbine has been supplied with two rows of velocity compounded impulse blading to absorb the large drop in the first pressure stage. The turbine and generator speed in the case of all the 1200-lb. units is 3600 rev. per min.

Both the straight tube boiler with headers and hand holes, and the multidrum bent tube boiler are being used to generate high-pressure steam. The straight tube boiler has the advantage of only a single drum; its many hand hole caps however have some drawback. The bent tube boiler as installed to date has three drums. The application of both types of boilers meant only a slight modification to take care of the higher stresses. The tube diameters have been decreased ¾ to one inch, while seamless forged drums have been substituted for the riveted construction possible with moderate pressure. Two "combustion steam generators" at the Philip Carey Manufacturing Company, Lockland, Ohio, will be used shortly to produce steam at 1840-lb. gage, the highest steam pressure to date in large boilers in this country.

Evolution of Boiler Types in Europe

Contrasted to standard boiler designs used in this country, European designs seem to indicate a desire to avoid exposing water and steam drums to the gases of combustion or piercing them with many holes in which tubes are rolled or expanded; headers in which tubes are expanded are also avoided. The fear of impure feedwater, with resulting scale deposits and burning of tubes, has led to two designs of indirect steam generation in which the heat absorbing parts contain steam only or else a circulating medium such as distilled, deaerated water. In three designs, small diameter tubing is used for primary heat absorption in order to minimize metal thickness and secure high heat transmission while retaining adequate wall strength. Minimum water content is considered essential, and the fear of disruptive explosions has also influenced the use of small tubes. In three designs external mechanical power is used to circulate water or steam over the heat absorbing surfaces to obtain positive cooling by preventing the lodging of steam bubbles or scale deposits on the tube walls.

The Atmos boiler designed by V. Blomquist employs boiler tubes about 12 in. in diameter with a wall thickness of $\frac{3}{4}$ in., rotating at 330 rev. per min. These tubes are driven by gearing at one end and rest in bearings outside of the boiler setting. Feedwater passes into the tubes through stuffing boxes at one end, while the steam is collected through similar stuffing boxes at the other end. The tubes extend across the boiler setting and are 11 ft. long. Water is forced against the tube walls by the rotation, while the separatory action causes the steam bubbles to collect in the center. The rotation of the tubes allows uniform heating stresses around the tube walls. The saturated steam produced in the tubes is passed through a convection superheater for further temperature elevation. The Atmos boiler has not been built for large commercial capacities, although the rate of evaporation per sq. ft. of heating surface is said to be high.

The Benson boiler in its latest installation consists of a vertical, cylindrical firebox formed by 16 tube sections connected in parallel to inlet and outlet manifolds. The tube sections are each formed of 450 ft. of continuous tubing having an outer diameter of 1.3 in. and a wall thickness of 0.25 in., and are made by welding together short tube lengths. Feedwater is pumped into the tube sections under 3200 lb. per sq. in. pressure, is heated as it flows through the tubes to 750 deg. fahr., and changes into steam without ebullition when the critical temperature of 706 deg. fahr. is reached. The steam flows from the outlet manifold through a reducing valve into a convection superheater.

In the Schmidt-Hartmann boiler primary steam is generated in a pipe coil exposed to the combustion products and flows to another coil immersed in a water and steam drum in which the secondary steam for use is generated by the absorption of the latent heat of the

primary steam. The condensed primary steam returns by gravity to the furnace coil after passing through a heat exchanger in which the feedwater to the secondary steam drum is preheated. Since the same water is circulated continuously in the primary circuit, no scale can form in the furnace tubes. The secondary steam generating drum is of simple construction with few openings. Impure feedwater can be used in the secondary generator without danger of overheating the steam coil in it. A convection type superheater is used to superheat the saturated secondary steam.

The Loeffler boiler employs steam for the circulating medium, but brings the primary and secondary steam into direct contact by blowing the superheated primary steam into the water in the secondary steam drum. The superheat in the primary steam causes the generation of additional steam in the water drum, and the total combined steam then is pumped mechanically through superheater coils exposed to the products of combustion. A portion of the superheated steam is returned to the water drum to continue steam generation there, and the balance is withdrawn from the system for use in prime movers or for heat.

Arrangement of High-Pressure Boiler Plant Heating Surfaces

There appear to be distinct variations in this country in the arrangement and proportioning of the several kinds of heating surfaces that make up a 1200/1400-lb. pressure boiler setting. The arrangement of heating surface does not appear to hinge upon the method of combustion and the thermal efficiencies of the different designs seem to be similar. Factors that are evidently important in this respect include the temperature of combustion gases as determined by the amount of furnace wall cooling and the boiler convection surface ahead of the reheater or superheater, and the necessity of reheating the steam exhausted from a high-pressure turbine element before it is passed to low-pressure turbines, thus requiring provision practically for two separate superheaters in the boiler setting.

In the bent tube multidrum boiler it is difficult to arrange both a high-pressure and a low-pressure superheater in the boiler gas passages, and both are located on the furnace walls for radiant heat absorption, as was done in the boiler at the Lakeside Station in Milwaukee, or the primary superheater is placed in the gas passages and the reheater element on the furnace wall, as illustrated by the two high-pressure boilers in the Northeast Station in Kansas City, Missouri. The effective surface of superheaters exposed to radiant heat can be much less than that of convection superheaters. The preferred arrangement at the present time in straight tube boilers seems to be a single-pass boiler consisting of a low bank of boiler tubes above the furnace followed in the gas path by the primary high-pressure superheater and the lower pressure reheater in series. Minimizing the number of boiler tubes decreases the amount of high

cost boiler parts, and allows a higher temperature head for heat transmission in the steam heaters.

A steam heated reheater is placed in series with the convection gas heated reheater in the Holland and South Amboy plants in such a manner that the low-pressure steam is first heated by saturated steam from the boiler drum, and then passed through the convection reheater. The use of high-pressure steam for reheating is convenient for automatic thermostatic control of the final steam temperature. The relative proportion of the reheating performed by the steam reheater decreases with the boiler rating in consequence of the increasing temperature of the combustion gases passing over the gas reheater, and the increased steam flow through the reheaters.

Air preheaters are being used to reduce to an efficient point the relatively high temperature of gases leaving the boiler or reheaters. Air preheater surface is inherently the cheapest that can be installed. An economizer is sometimes included ahead of the air preheater to temper the gases entering the air heater, even though the feedwater temperature may run above 400 deg. fahr. Sizable economizers are employed in the Boston, Holland, Deepwater, South Amboy, and Kansas City plants, and will also be installed with the Philip Carey Mfg. Co. "steam generators." This last development will deliver steam at 800 deg. fahr. to triple-expansion reciprocating engines exhausting around 60-lb. gage to supply manufacturing process requirements. No economizer is used on the Milwaukee boiler which has a low stack temperature as the result of a completely metal cooled furnace and a deep banking of boiler tubes baffled for three effective passes.

The general proportioning of heating surfaces in typical high-pressure boiler installations is shown by the following table, but these figures must not be considered as comparable since they include different types of heating surface of varying degrees of effectiveness.

TABLE I
ARRANGEMENT OF HEATING SURFACES IN TYPICAL HIGH-PRESSURE BOILERS

Plant	Edgar	Holland	Northeast	Lakeside
	Boston		Kansas City	Milwaukee
Type of boiler	Cross-drum Straight tube	Cross-drum Straight tube	Multidrum Bent tube	Multidrum Bent tube
Total convection surface sq. ft.	58,302	66,066	69,761	68,852
Boiler surface—per cent conv. surf.....	12.0	12.0	24.3	41.4
Superheater surface—per cent conv. surf.....	8.7	6.9	3.8	..
Gas reheater surface—per cent conv. surf.....	11.9	17.2	..	..
Economizer surface—per cent conv. surf.....	16.5	17.6	15.6	..
Air heater surface—per cent conv. surf.....	50.9	46.3	56.3	58.6
	100.00	100.0	100.0	100.0
Water wall surface—per cent conv. surf.....	2.1	..	4.4	2.2
Radiant superheater—conv. surf.....	..	..	..	2.7
Radiant reheater—conv. surf.....	..	..	0.7	1.4
Steam reheater—conv. surf.....	..	2.2	..	..

Cost of High-Pressure Steam-Electric Stations

A full discussion of the net economic benefit derived from high pressures has been published in the 1928

Transactions of the American Society of Mechanical Engineers. The engineers who have developed the use of 1200-lb. steam in actual plants show in comparison to 400-lb. installations debit charges against the water and steam equipment actually handling the high pressures, but preponderant credits for thermal saving and capacity available. The possible increase in capacity is believed by some engineers of high-pressure experience to offset the higher equipment charges resulting in an initial cost no greater than that of a standard 400-lb. plant.

Summary Description of High-Pressure Plant Installations

Plants with two boiler-pressures.

Edgar—Boston. Now has one 3150-kw. single-valve turbine, one 10,000-kw. single-valve machine, and one 12,500-kw. multi-valve machine.

Lakeside—Milwaukee. Now has one 7000-kw. and one 7700-kw. machine, both being single-valve turbines.

Northeast—Kansas City. Has a 10,000-kw., turbo generator. The high-pressure turbines in these plants exhaust into low-pressure station steam mains at pressures of 300 to 350 lb., and are really high-pressure turbine elements superposed upon distinct lower pressure stations.

Plants with single boiler-pressure.

In these plants the entire low-pressure steam requirements will be supplied through the high-pressure turbines and from high-pressure boilers only, there being no steam generation except at 1400 lb.

Holland. This station at Holland, New Jersey, on the Delaware River contains initially one cross-compound turbo generator of 55,000-kw. capacity, consisting of an 11,800-kw. high-pressure element operating at 3600 rev. per min. and a 43,200-kw. low-pressure element operating at 1800 rev. per min. with a direct-connected exciter to supply both generators. Two

boiler units supply steam at 1400 lb. and reheat the steam intermediate between the high- and low-pressure turbine elements. Both boilers have primary steam

reheaters in series with convection type gas reheaters. The boilers are fired with pulverized coal by the bin system, using horizontal burners for opposed firing, and each generates 250,000 lb. of steam per hour. Full-load feedwater temperature is 443 deg. fahr. and the steam temperature 750 deg. both initially and after reheating at 400 lb. For further description see *General Electric Review*, Vol. 32, No. 2, Feb. 1929.

Deepwater—Wilmington. This plant contains two 53,000-kw. cross-compound units consisting of a 12,500-kw. 3600-rev. per min. high-pressure element, and a 41,700-kw. 1800 rev. per min. low-pressure element. Each generator of a unit has a direct connected exciter. The exhaust steam of a third high-pressure turbine unit supplies an industrial establishment nearby. Reheating is done by only two of the six high-pressure boilers, following the practise in plants of 600 to 700 lb. where reheating between turbine elements has been necessary. Comparison of the standard and reheat boilers is as follows:

	Standard boiler	Reheat boiler
Capacity.....	330,000 lb. per hr.	290,000 lb. per hr.
Steam temperature.....	725 deg. fahr.	725 deg. fahr.
Boiler surface—straight tube....	9,000 sq. ft.	9,000 sq. ft.
Reheater surface—gas.....	..	23,562 sq. ft.
Economizer surface.....	18,326 sq. ft.	4,763 sq. ft.
Air preheater surface.....	43,600 sq. ft.	52,800 sq. ft.

Three of the boilers are fired by unit mills, and three by the bin system.

South Amboy. This plant on the Raritan River in New Jersey will contain two cross-compound, double-deck type units each consisting of a 5100-kw., 3600-rev. per min. high-pressure element located above a 19,900-kw. 1800-rev. per min. low-pressure element. Three boilers fired by unit type pulverizing mills will supply 250,000 lb. per hour of steam each at 1310 lb. and 750 deg. fahr. The boiler arrangement will be as follows:

Boiler.....	7,250 sq. ft. heating surface
Gas reheater.....	12,900 sq. ft. heating surface
Steam reheater.....	2,190 sq. ft. heating surface
Economizer.....	4,420 sq. ft. heating surface
Air preheater.....	32,050 sq. ft. heating surface

Station A—San Francisco. The throttle pressure for two 50,000-kw. cross-compound, double-deck turbo generators will be 1200 lb. at a temperature of 750 deg. fahr. Steam will be obtained from "standard" boilers having a maximum capacity of 400,000 lb. per hour each, and from reheating boilers of a maximum capacity of 440,000 lb. per hour.

PRESENT LIMITS OF STEAM TEMPERATURE

There does not seem to be any widespread effort to use steam for power generation at temperatures higher than customary for the past several years. This does not imply that the thermal gains to be derived by higher steam temperatures are not apparent, nor that the investigation of metals to withstand higher temperatures is not being actively carried out. The limiting temperature at the present time generally

recognized in this country is around 750 deg. fahr. although instances of operation at slightly higher temperatures have been reported. A straight expansion to vacuum of steam at this temperature without excessive wetness loss in the low-pressure end of a turbine is possible only with steam pressures up to 450 to 500 lb. Above 600 lb. it has been necessary to reheat the steam between turbine elements. A higher initial steam temperature would permit higher initial pressures for direct expansion, as well as increase the available thermal saving for any particular pressure, either with or without reheating. The equipment subject to the highest temperature includes a part only of the superheater, the steam piping and valves, and one end of the turbine. Alloy steels are available which appear capable of withstanding the temperature required to give a steam temperature measurably higher than present practise. Valve and piping manufacturers are more optimistic than the turbine manufacturers who are not now guaranteeing constructions for more than about 800 deg. fahr. At high pressures an appreciable metal section is required to withstand the pressure stresses, and this in turn leads to additional thermal stresses arising from the differential temperatures. The rate of "flow," or "creep," of metals when under high temperature and stresses also appears to be causing some conservatism in the design stresses for which boiler and superheater parts are proportioned.

LARGE BOILER DEVELOPMENTS

Perhaps the next most significant trend in steam plant design is the effort to bring the number of boiler units in line with the number of turbines installed in a plant. Primarily the object is the reduction of first cost of the boiler plant, but there is also some saving in operating labor and maintenance costs. The decrease in the number of boiler units is being brought about both by the use of units of greater heating surface as well as effective absorbing capacity, and by operation at higher average ratings. Greater evaporative capacities have depended upon the ability to burn sufficient fuel under the boiler, but this requirement disappeared with the development of pulverized fuel; the underfeed stoker in turn was stimulated in its performance and fuel burning capacity. Water and steam cooling of the furnace walls removed the refractory limitation to higher combustion rates and increased the availability factor of the boiler unit; other efforts to this end have been directed toward the prevention of clogging of the entrance of the first pass of boiler tubes by slag and combustible in the furnace gases. With feedwater containing no scale forming matter, there is reason now to expect an availability factor for the boiler proper approaching that of turbo generators. Another factor holding down the number of boilers is the tacit, as well as stated, recognition that it is economically justifiable to shift station loads on an interconnected system whenever cleaning or inspection of a large boiler unit is necessary.

Description of Large Boiler Installations

East River. The largest boilers in the world, now being installed in the East River Station of the New York Edison Company, have a maximum generating capacity each of 800,000 lb. per hour, at a working pressure of 425 lb. per sq. in. and 725 deg. fahr. total temperature. These boilers will be of the bent tube A type setting, having two lower boiler water drums, and two lower economizer section drums; at the top of the boiler there will be four water and steam drums; while above these will be two additional dry drums of 48 in. diameter; the boiler drums are 54 in. in diameter. The furnace has a plan section of 23 ft. 6 in. by 43 ft., and a volume of 38,200 cu. ft.; it is entirely water cooled. Pulverized coal is fired on two sides, both vertically and horizontally. The maximum rate of heat liberation is 25,300 B. t. u. per hour per cu. ft. of furnace volume. The heating surface areas are as follows:

Boiler heating surface.....	60,706 sq. ft.
Water wall heating surface.....	6,765 sq. ft.
Superheater surface.....	8,100 sq. ft.
Air preheater (in two units).....	91,728 sq. ft.

The expected stack gas temperature at a steam output of 800,000 lb. per hour is 360 deg. fahr.

Hell Gate. Two boilers have been ordered for the Hell Gate plant of the United Electric Light and Power Company of New York, that will each supply a maximum of 800,000 lb. of steam per hour at a pressure of 275 lb. and a temperature of 725 deg. fahr. Each boiler will consist of one pair of cross-drum boilers with 20-ft. tubes set end to end with the high end headers adjacent to each other above the center of the common furnace. Each half section of a boiler will have its own 72-in. drum, interdeck superheater, economizer, air preheater, and furnace water wall. The circulation and steam connections of each boiler in the twin setting will be entirely independent. The furnace will be fired with pulverized coal from unit mills, lined on four sides with water walls, and arranged for disposal of ash in molten form. The two boilers will supply enough steam for a 160,000-kw. turbo-generator unit.

Delray. Five boilers using underfeed stokers are being installed in the Delray No. 3 plant of the Detroit Edison Company, that will have a normal continuous capacity each of 350,000 lb. of steam per hour at a working pressure of 455 pounds and a temperature of 725 deg. fahr. The boilers are of the four drum bent tube type, being 53 tubes wide and using $3\frac{1}{4}$ in. tubes. The furnace walls are entirely water cooled; a slag screen of two tubes depth extends across the top of the furnace several feet below the entrance of the first pass proper. The water walls and slag screen are connected to a separate drum in the manner previously developed at the Trenton Channel plant of the same company. The division of heating surface is as follows:

Boiler heating surface.....	23,900 sq. ft.
Water wall and screen surface.....	3,494 sq. ft.
Superheater surface.....	4,900 sq. ft.
Economizer surface.....	6,032 sq. ft.
Air preheater surface.....	30,200 sq. ft.

The stoker is 15 retorts in width and 57 tuyeres long, and occupies with the double roll clinker grinder a distance between front and bridge walls of 23 feet. The preheated air supplied to the stoker for combustion purposes will not exceed 350 deg. fahr. at maximum rating.

San Francisco. Two 2225-hp. boilers for 450 lb. and 625 deg. fahr. steam are being installed in the plant of the Great Western Power Company, where they will operate at low use factor but will be called upon to pick up load at times quite suddenly. The boiler construction consists of a 72-in. diameter cross-drum 40 ft. long connected to a bank of tubes 56 wide by 13 high, with a supplementary dry cross-drum 36 in. in diameter and 30 ft. long mounted 11 ft. above the main drum and connected to it by 45 four-inch tubes; two steam purifiers will also be installed in each boiler to limit the moisture carry over upon sudden steam demands. The 35,000-kw. turbo generator that will be used frequently as a synchronous condenser for voltage regulation and for standby service, is valved so that it can carry full load with a steam pressure as low as 235 lb. The furnaces fired with fuel oil, are equipped with 9 pilot burners and 20 main burners, and when operating at 5 per cent of normal rating the boilers will be able to pick up full turbine load suddenly applied with a pressure drop of only 125 pounds before the main burners can be brought into operation.

Gorgas. At the Gorgas steam plant of the Alabama Power Company a 60,000-kw. turbo-generator unit is being served by two boilers each of 30,315-sq. ft. heating surface, equipped with air preheaters of 30,600-sq. ft. area and superheaters that give a final steam temperature of 740 deg. fahr. at maximum boiler output of 450,000 lb. per hour. The boiler drums built for 475 lb. are 72 in. in diameter and 34 ft. $2\frac{3}{4}$ in. in length, being the largest riveted drums to date for this pressure. The 4-in. tubes 24 ft. long are arranged 51 wide by 20 high. The furnaces are fired with pulverized coal. The induced draft fans are operated by two motors, one of 900 hp. which will provide draft up to a steam output of 380,000 lb. per hour, and a larger motor of 1800 hp. for an output of 450,000 lb. A 700-hp. motor drives the forced draft fan supplying air to the furnace through the preheater.

FURNACE WALL COOLING

Trends in the method of combustion and in furnace design that were probable two years ago have been rather conclusively confirmed in many instances. At the present time there are instances of metal cooling the entire furnace wall surface of large steam boilers to the virtual exclusion or absence of the ordinary types of refractories. This applies to underfeed stoker fired furnaces as well as to pulverized coal furnaces. The extent of metal cooling in furnaces fired with traveling grate stokers does not appear to be of such broad application as the result of the losses arising from retarded

ignition and a generally lowered furnace temperature. There are cases of station enlargement where the original furnace settings were entirely refractory, but additional boilers were provided with metal cooled furnaces so that comparison of available capacities and maintenance costs have been secured. The experience at the Cahokia plant of the Union Electric Light and Power Company of St. Louis was reported by E. H. Tenney in this respect in the October 1928 issue of *Mechanical Engineering*, as well as with regard to changes in the combustion method that will be discussed later. Metal cooling of the furnace seems to be practically necessary when any appreciable heat recovery is effected by air preheaters; the introduction of preheated air in turn contributes to better firebed conditions on stokers and serves to maintain a high combustion rate in pulverized fuel furnaces; and higher ratings seem to be obtainable with decreased furnace wall maintenance through the extensive use of metal cooling. The majority of the large boiler furnaces recently put in operation have been metal cooled, and well-known cases of replacement of refractory lining with metal walls have also occurred. Under the term of metal walls several types of construction are to be included, such as plain boiler tubes on the face of, or embedded in a refractory wall, boiler tubes of the fin type backed up with a heat insulation, and boiler tubes with plain metal or refractory faced blocks clamped to them.

STOKER DEVELOPMENT

The development of underfeed stokers in the past two years has been directed mainly toward an increase in burning capacity per foot of width, principally through lengthening the coal feeding area by extending the retort zone, with an additional number of tuyeres through which the air for combustion is delivered. Stokers having 65 tuyeres are now being built. Further travel from the front of the stoker to the rear is obtained in some designs by the addition of an overfeed section between the end of the retort and the edge of the clinker grinder pit, as illustrated by the last stokers installed in the Hudson Avenue plant of the Brooklyn Edison Company that have an overfeed section approximately six feet in length. While the increase in length of stokers has been the most notable development in stoker design, stokers up to 35 ft. in width have also been built. The relative decrease in the width of the stoker for a given stoker area that has resulted from lengthening of the stoker, has brought about an advantage of secondary importance by the reduction possible in banking fuel, since combustion during banking occurs almost wholly along the front of the stoker.

Progress has been made recently in adapting the rotary ash discharge type of stoker for the efficient burning of low grade fuels in quantity, mainly by improved design of the clinker grinder pit and grinder rolls along the ideas developed in stoker practise with higher grade eastern coals.

The long travel of the coal and waste products from the coal hopper to the grinder pit has required facilities for adjusting the motion of the different parts of the firebed and for individually controlling the windbox pressures under the subdivided stoker sections. These mechanical requirements are reflected in the trend of development toward the wider use of steel and of parts machined or cast to specifications not before justifiable.

CHANGES IN PULVERIZED FUEL PRACTISES

The increasing use of pulverizing mills delivering their product directly to the furnace, and the horizontal arrangement of burners for combustion are the most outstanding trends in pulverized fuel practise. The pulverized method of combustion has been applied on a large scale to almost every kind of coal commercially available in the country. The initial cost of pulverized fuel equipment external to the furnace has been reduced by placing the pulverizing mills adjacent to the furnace and by drying the coal in the mills during pulverization, thus minimizing building volume and conveying and drying equipment; when the coal is then delivered from the mills to the furnaces without the interposition of costly bunkers, further simplification of equipment is possible. In one mill arrangement the fan for transporting the coal from the mill to furnace is integral with the mill; in another layout a separate fan is placed between the mill and the bunkers. Heated air from the flue gas air-preheater is ordinarily employed for mill drying, although steam air-heaters are installed in some plants. Direct firing without fuel storage between the mill and burners requires division of the mill capacity, as well as burner equipment, into two or more units in order to insure a certain degree of reliability of fuel supply. Duplication of mills is also a benefit for the control of fineness of the pulverized product with varying boiler ratings; mill power can also be controlled to some extent. A census made by the Prime Movers Committee of the National Electric Light Association showed that for recent installations the ratio of direct fired to bin and feeder boiler horsepower was 1.7 to 1 for utility plants, and 9 to 1 for industrial plants. The average size of boilers fired by the unit system appears to have increased in the last two years, with the size of direct fired boilers in utility plants still being considerably larger than boilers similarly fired in industrial boiler plants.

The trend towards horizontal firing seems to coincide with the attempt to increase the average heat liberation per cu. ft. of furnace volume. Horizontal firing has been used with both the bin and unit mill systems, being particularly convenient with unit mill layouts, although both horizontal and vertical firing have been applied together in the same furnace. Horizontal burners having relatively large coal capacity lend themselves to the use of forced draft which must be employed for the maximum of turbulence, an essential for horizontal firing. In some cases where the ash deposited on the

bottom of the furnace is removed in a molten state, the temperature at the furnace hearth must be maintained above the fusing temperature of the ash, which is readily done by burners located near the bottom of the furnace.

Turbulent firing and metal cooling of furnace walls have led to a method of ash removal which seems likely to be exploited in new installations. It is possible to maintain temperatures at the floor of the furnace sufficient to liquefy ash having fusion test temperatures up to 2500 to 2600 deg. fahr. Means for readily removing liquid ash from the furnace and disposing of it have been devised at the Charles R. Huntley Station of the Buffalo General Electric Company, and the method is being applied at other plants. The furnace floors in "slag bottom" furnaces are horizontal, and the slag is tapped out at intervals into a stream of high velocity water that shatters the slag and disintegrates it into small particles that can be handled hydraulically.

The effect of extensive water and steam cooling of furnace walls together with turbulent firing may be seen from a comparison of the maximum rates of heat liberation in some of the recently constructed furnaces, with conditions existing in the latter part of 1927 in pulverized fuel installations. The Prime Movers Committee of the National Electric Light Association at that time published a tabulation of pulverized fuel installations covering 224 furnaces fired by the bin and storage method and 166 fired by unit type mills, for which heat liberation data were known. The arithmetical average maximum liberation of B. t. u. per cu. ft. of furnace volume per hr. was 20,300 and 21,400 for bin and unit systems respectively. The frequency distribution for the two cases, however, was quite different, the modal value or the figure of greatest frequency being 16,400 for the bin system and 21,800 for the unit system. Compared to these figures of heat liberation, the last furnaces installed in the Cahokia plant of the Union Electric Light and Power Company of St. Louis will have a maximum rate of 26,700 B. t. u.; the recent furnaces in the Hell Gage station of the United Electric Light & Power Company of New York, 35,000 B. t. u.; and the last installation at the Charles R. Huntley station of the Buffalo General Electric Company, a liberation of 37,900 B. t. u. per cu. ft. per hour. The furnaces in these three stations are being fired from unit mills and with horizontal burners, the furnace walls being completely metal cooled.

COMPARATIVE STATUS OF PULVERIZED AND STOKER FIRING METHODS

The introduction of pulverized fuel firing less than ten years ago has been followed by its application in all sizes of boiler plants and with all classes and grades of lignite, bituminous, and anthracite coals. Experimental installations on a large scale and commercial competition with stoker firing, have now continued

long enough perhaps to allow a generalized comparison of the two methods.

There seems to be a recognition that most of the earlier pulverized installations have been slightly higher in first cost than corresponding stoker plants, but the operating advantages claimed for pulverized firing appeared to overbalance any cost differential in favor of stokers. There can be no question that the increased use of pulverized firing stimulated new developments in stoker design with the result that fuel burning capacity, range of high efficiency, etc., of stokers, were greatly broadened, and thereby a more effective competition with some of the major advantages of pulverized firing was created. During the same period the apparatus layout for drying, pulverizing, and burning coal was simplified with an apparent reduction in first cost.

Whereas formerly there was a widespread belief that a much greater choice of fuels was available for pulverized firing than could be utilized by any one type of stoker, recent developments in the stoker field have narrowed this advantage to special cases of extreme variations in fuel supply, such as anthracite and bituminous. With coals for which the underfeed stoker has been most extensively applied, the operating advantages of pulverized firing are looked upon as rather debatable by some engineers. Smaller banking losses, greater flexibility with fluctuating loads, and better sustained efficiency over a wider range of loading, have been claimed for pulverized firing, as well as better adaptability for complete automatic control. Opposed to these claims the disadvantage of greater dissemination of ash dust to the atmosphere is cited. Certain it is that the ash dust problem is real and its total elimination appears to be quite costly. In a recent case the greater commercial possibilities in the disposal of stoker ashes over pulverized fuel furnace ash was one of the factors that influenced the selection of the combustion method. There are many engineers who believe that with an assured fuel supply of good and uniform grade, there is so little difference in net economic results between the two combustion methods that the choice in particular cases is being made for reasons which formerly were regarded as subordinate considerations.

LARGE TURBO-GENERATOR INSTALLATIONS

Increase in capacity of turbine cylinders and generators still continues to be the most impressive development in the steam turbo-generator field, although turbine units of immense size have not been uncommon or unpresaged in the past. It is probably correct to say also that the growth in capacity of individual units has been made possible, not by any new or radical ideas, but by refinement and application of design principles already at hand. The 208,000-kw., three-element, cross-compound General Electric machines for the State Line Plant near Chicago, announced some two

years ago, remain the largest units in total capacity on record. Previous records, however, have recently been broken for two-element cross-compound units, and for single-element machines. The 160,000-kw. machine that is going in the East River Station of the New York Edison Company will embrace both the largest tandem-compound turbine and the largest generator ever built. Generators of large capacity are now operating at 22,000 volts in this country and at 33,000 volts in England, which is believed to be the highest voltage used to date for large power generation.

Two-Element Cross-Compound Turbines

Hell Gate. The two turbo generators of 160,000-kw. capacity each recently installed in the Hell Gate plant of the United Electric Light and Power Company, New York City, consist of a single flow high-pressure element and a double flow low-pressure element. One was manufactured by the American Brown Boveri Company and the other by the Westinghouse Electric and Manufacturing Company. Machinery details are as follows for the two units:

	A. B. B. Co.	W. E. & M. Co.
Rated capacity, H. P. section . . .	75,000-kw.	80,000-kw.
L. P. section . . .	85,000-kw.	80,000-kw.
Speed, H. P. section . . .	1,800-r. p. m.	1,800-r. p. m.
L. P. section . . .	1,200-r. p. m.	1,800-r. p. m.
Electrical conditions	85 per cent p. f., three-phase, 60 cycles 13,800 volts	
Steam conditions	265 pounds, 611 deg. fahr.	

The 137,500-sq. ft., two-pass horizontal surface condensers serving these turbines are unique in their arrangement, each consisting really of two separate condensers attached to the two exhaust nozzles of each low-pressure turbine, but having a common central waterbox horizontally divided for inlet and outlet condensing water. One-half of the condenser is rigidly attached to one exhaust nozzle while the other section of the condenser is joined to the other exhaust nozzle by a flexible joint with lateral freedom.

Single-Element Turbines

The single cylinder General Electric units of 75,000-kw. capacity each in the plants at St. Louis and Buffalo are the largest machines to date of that type. The Cahokia, St. Louis unit is an 1800-rev. per min., 60-cycle machine operating on steam at 315 lb. and 725 deg. fahr., while the Buffalo unit is a 1500-rev. per min., 25-cycle, 275-lb., 689-deg. machine. It is to be noted that while the high pressure element of the State Line unit is rated at 76,000 kw., the expansion of steam through it is only partial, as contrasted with the complete expansion to 29 in. vacuum in the single cylinder machines of 75,000-kw. rating.

Tandem-Compound Turbines

East River. The 160,000-kw. tandem-compound General Electric machine being installed in the East River Station in New York will have a two-winding generator, the circuits of which are entirely separate

and coupled only by the mutual reactance between them. The windings will be connected to separate bus sections whose only tie normally will be through the transformer action of the two windings in the generator. The advantages of the two-winding generator include the use of smaller switches than would have been necessary to handle the entire generator output, and led to a bus arrangement whereby short-circuit disturbances are localized and minimized; switch house building space was saved; a ground on one winding will not require taking the other winding out of service; and the bus tie through the generator will result in synchronism of the two bus sections during disturbances, since the two windings must necessarily be in synchronism, although effective reactance between the busses still exists. The generator is a three-phase, 25-cycle, 11,400-volt machine, operating at 1500 rev. per min. Throttle steam conditions are 400 lb., 725 deg. fahr. Further details regarding this installation may be found in *Electrical World*, Vol. 92, No. 24, Dec. 15, 1928.

GENERATOR VOLTAGES AND SPEEDS

There was an advance in voltage of large generators when the 94,000-kw., 1500-rev. per min., 16,500-volt unit went into service in the Long Beach Plant No. 3 of the Southern California Edison Company. This voltage is now exceeded in the 55,000-kw. turbo generator in the Pekin, Illinois, plant of the Super-Power Company, that operates at 22,000 volts and 1800 rev. per min. In England a 25,000-kw., 80 per cent power factor, 3000-rev. per min. machine, that generates at 33,000 volts, has been recently put in service in the new Brimsdown plant, and is believed also to represent the highest capacity developed to date above 1800 rev. per min. In this country the 12,500-kw. 80 per cent power factor generators, driven at 3600 rev. per min. by the 1200-pound turbines, mark the peak capacity of high speed machines produced to date.

TURBINE AUXILIARIES

There have been no outstanding new trends within the past two years in the design of condensers or other auxiliaries serving turbo generators; neither have there been any new developments in the methods of heating and deaerating boiler feedwater. The trend toward the use of single-pass condensers, and a lower ratio of condenser surface per kilowatt of turbine capacity seems to be confirmed in practically all of the newer stations. Feedwater heating by steam extraction is almost universal.

The necessity of pure feedwater for the higher pressure boilers is perhaps leading to increased efforts toward the reduction of condenser leakage by attaching the condenser tubes to the tube sheets in the manner in which boiler tubes are "rolled" or "expanded." In some cases the tube sheets are flexibly connected to the condenser shell, while in one instance the condenser tubes have been bowed in order to allow them to deflect laterally if necessary.

The cooling of generators by the enclosed circulation system is now widely practised in steam electric stations, and is also being extended to waterwheel generators. Hydrogen in place of air for cooling has also been used in the case of a synchronous condenser, that is installed in the open with a weatherproof casing.

MERCURY VAPOR DEVELOPMENTS

The mercury vapor boiler and 10,000-kw. turbine installation at the South Meadow Plant of the Hartford Electric Light Company, Connecticut, described in the last report, was placed in operation in October, 1928. Mercury vapor is produced at a temperature of 884 deg. fahr., passed through the mercury turbine and condensed at 28 in. of vacuum to make steam at 350-lb. pressure. The steam is returned to the boiler setting and superheated from 436 deg. to 700 deg. fahr. before going to the station steam mains. A water economizer and air preheater following the steam superheater in series reduce the flue gas temperature to 280 deg. fahr. A mercury heater or economizer is located between the mercury boiler and steam superheater. The furnace is fired with pulverized coal.

STEAM TABLE RESEARCH

The experimental results from the A. S. M. E. Steam Research Program carried out during the past few years at Harvard University, the Massachusetts Institute of Technology, and the U. S. Bureau of Standards, have given a mass of overlapping data that has enabled the General Electric Company to develop a complete set of steam tables and diagrams to 3500 lb. per sq. in. and 1000 deg. fahr. These were published in preliminary form in the February 1929 issue of Mechanical Engineering. The remarkable agreement between the experimental results, and with contemporary foreign data, indicates that the new tables will suffice for the most exacting type of engineering work.

ACKNOWLEDGMENT

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REPORT OF SUBCOMMITTEE ON EXCITATION IN ELECTRIC POWER PLANTS

A survey has been made of the excitation layouts in some 26 modern large stations, the majority of which have been in operation less than five years. The generating units in these stations range in individual capacity from 12,500 kw. to the largest yet operated. The frequency of application of the salient features of excitation layouts is shown by the following tabulation, which, though not including all modern stations, yet is believed to be representative of present day practise.

Design feature	Relative application
Excitation voltage of 230-250.....	100 per cent
Systems individual to a generator.....	93 per cent
Individual systems with transfer bus to spare excitation capacity.....	81 per cent
Individual systems having battery spare.....	27 per cent
Individual systems using motor-gen. exciters driven from shaft generators.....	11 per cent
Individual systems using sub-excitation of exciters.....	33 per cent
Installations using shunt windings on main exciters.....	87 per cent
Installations omitting main field rheostats.....	50 per cent

An excitation voltage of 250 has been adopted almost universally because of the economy of copper and switch facilities, and the fact that reliability is readily obtainable with 250-volt machines operating at the main generator speed, usually 1800 rev. per min. or less.

Excitation sources arranged individually for each generator predominate constituting 93 per cent of the cases. Only one station surveyed operates on the central system with excitation busses supplied from separately driven station exciters; one station uses group excitation busses supplied from shaft-end exciters belonging to the machines excited from the group bus.

Individual excitation is obtained from shaft-end exciters in 89 per cent of the cases, there being three instances only in the group surveyed of motor-generator exciter sets supplying excitation on the individual principle. In these cases the motor-generators were driven from shaft-end generators mounted on relatively slow-speed hydro units, and were used primarily in the interest of quick response excitation.

However, of the individual excitation systems, 81 per cent of the installations have available transfer facilities whereby spare exciters or storage batteries can supply the fields of the generators in the event of loss of the shaft-end or motor-generator exciters. Storage battery reserve is provided in 27 per cent of the individual systems, but it is noted that in operation these batteries are not paralleled with the individual sources of excitation.

In 33 per cent of the cases, sub-excitation or separate excitation of the main exciter is provided by a pilot exciter carried on the shaft of the main exciter, both shaft-end and motor-generator exciters. In one large station, however, the main generator fields are excited in parallel from group sub-excitation busses that are energized by small motor-generator sets and storage batteries. In all instances except this, the sub-excitation installations are used in connection with transmission line systems.

Shunt windings only on the main exciters seem to be preferred in 87 per cent of the cases.

The elimination of the main field rheostat in 50 per cent of the cases, or its installation for emergency operation and the control of the main generator voltage by means of the exciter voltage appear to have advantages desired by quite a few engineers.

Manual control of the main generator voltage still seems to be favored, particularly in steam-electric

stations, although a number of plants has installed and operates automatic-control equipment.

Where generator voltage is to be maintained during system disturbance, automatically-operated quick-response equipment has been installed. The individual exciter makes the high-speed excitation problem simpler, as a central excitation system, with machines of different size and characteristics, could not be regulated satisfactorily even though all generators might be feeding a common bus at the time of a disturbance. With the individual exciter, the main generator voltage can readily be controlled by varying the main exciter rheostat or by a pilot exciter. Thus the main field rheostat may be entirely omitted and by the use of special relays and reversed windings on the exciters, a wide range of excitation may be obtained. Quick response excitation is obtained by suitable design, principally by the use of parallel field circuits and laminated magnetic circuits. The quick-response installations have found their widest application to hydroelectric systems in which the machine and line reactance are relatively high and stability is important. With large networks connected to widely separated steam and hydro plants, quick-response excitation may be desirable for steam-driven generators and its installation should be the subject of a careful analysis of the transmission and generating conditions. High speed as referring to excitation is somewhat indefinite, but in the present state of the art, implies a voltage increase of 400 to about 700 volts per second with 250-volt excitation. The developments in design of d-c. exciters have been such that today, even on low speed hydro generators, a satisfactory direct-connected exciter can be built at a cost little, if any, greater than for a separate motor driven exciter installation.

One company has installed quick-response excitation on a steam-driven house generator of 5000-kw. capacity to maintain voltage with sudden load changes such as occur when starting or shutting down the large motor-driven auxiliaries. Synchronous condensers are also equipped with quick response excitation and on account of the relative capacity of the synchronous condensers and the system it may be desirable to have the response quicker than for the generator.

One company now studying means for insuring the reliability of the excitation layout for steam-driven machines of 100,000-kw. capacity, is considering the use of two separately insulated field windings for the main generator, with each winding magnetically balanced so that the machine can operate safely with either field winding alone, and each field winding to be capable of operating the generator at approximately unity power factor. Independent sources of excitation are to be used for each field winding, and there are to be automatic means for increasing the strength of one field winding in case the voltage on the other fails.

REPORT OF SUBCOMMITTEE ON AUXILIARY DRIVES IN ELECTRIC POWER PLANTS

Present practise with regard to auxiliary drives has been summarized below from the data obtained from a list of some 21 modern stations. These data are believed to be sufficiently comprehensive to be representative. The generating units in these stations range in individual capacity from 12,500 kw. to the largest yet operated.

General

Motor drive of auxiliaries is used in all cases except one in which steam drive is the main auxiliary power. However, the installation of a steam-driven boiler feed pump for reserve purpose appears to be universal, while in a small number of cases duplicate motor and steam drives are used for some of the more necessary auxiliaries.

In approximately half of the stations, the auxiliary layout is designed and operated on the unit system, *i. e.*, each turbo generator and its corresponding essential auxiliaries form a unit.

METHODS OF POWER SUPPLY

The sources of auxiliary power and their relative use are shown by the following tabulation.

Source of auxiliary power	Relative use
Transformers ahead of generator switch.....	22 per cent
Generators on main unit shaft.....	22 per cent
Installations of house turbines.....	39 per cent
Transformers on busses or supply from other stations	universal

Transformers connected ahead of the generator switch assure energy whenever the main unit operates and with proper protection by relays and oil switches, line disturbances will not cause an outage of auxiliary power. However, in the case of machines feeding a large system, operating conditions may be such that the machine voltage, and consequently the auxiliary voltage, vary between unduly wide limits.

The shaft generator has the advantage of isolation, and insures an auxiliary supply whenever the main unit is running. For starting up, the auxiliaries can be thrown upon the emergency bus, or normally open tie switches can be closed. The shaft generator increases the space required for the unit substructure and foundation and adds somewhat to the unit cost. It has the disadvantage that electrical or mechanical failures may require a shutdown of the main unit for repair.

The house generator, driven by a separate steam turbine, provides a maximum of separation and with a standby machine or motor-generator set should meet the requirements from the standpoint of reliability. As the trend today is towards large units, the auxiliary power demand for turbine and boiler unit is passing beyond several thousand kilowatts, and the turbines, especially if of the 3600-rev. per min. design, may be built with good steam rates, materially lessening the

advantages of the shaft-driven generator which operates at speeds of 1200 to 1800 rev. per min.

Special windings on the main generator are being considered, but as the auxiliary voltage would be dependent upon the main field excitation, and this would be varied in accordance with the system demands, it is necessary to provide a suitable arrangement to hold the auxiliary voltage reasonably constant. It has the disadvantage that failures in either stator winding may be communicated to the other winding and result in having the main generator out of service for slow and expensive repairs.

Motor-generators a-c. to a-c. may be used instead of transformers, but they introduce additional rotating machinery which requires more attention, is more liable to fail and more expensive than transformers.

The motor-generator set or house-generator are the two logical solutions for d-c. auxiliary power. The recent developments in rectifiers for railway service may result in their application in power stations. A synchronous converter of course could be used instead of a motor-generator set, but it does not provide complete electrical separation of a-c. and d-c., does not give the voltage range, and is not inherently as stable as the motor-generator set.

Types of Motors

For some apparatus the wound-rotor motor is particularly well adapted. If the speed range does not exceed approximately 40 per cent, the commercial types of control apparatus, with a multiplicity of speed points, may be employed. For a speed range comparable to that of a d-c. motor, double-winding slip-ring motors are available, but the control gear becomes unduly complicated and expensive, and the motor is special, so that first cost and replacement are high. The brush shifting motor is liable to spark, is expensive and higher in maintenance than other types. Its commercial size is limited, and it is not available for some of the large auxiliaries of the new stations.

D-c. motors lend themselves readily to a wide range of speed control with little sacrifice in economy and with relatively inexpensive control equipment. The commutator motor is not desirable for a dusty or gassy atmosphere, but then the machines may be totally enclosed and vented from the outside. In order to insure stability of motor operation the d-c. motor for wide speed ranges should be designed for a substantial ampere-turn excitation over the whole range.

For the usual plant, 2300-volt motors are used above 50 hp., and below this, 440 or 220 volts are well adapted, as it makes available the large stocks of the motor manufacturers. The selection of the auxiliary voltage and changeover motor size cannot be governed by any hard and fast rule, but should be the basis of study for each installation, considering not only the economics but also reliability and simplicity.

The central station is built up around reliability of

service, and this is materially aided if special insulation, that is, better than the commercial standards, is used on the station auxiliaries.

The synchronous motor has not found a wide field of application in the power plant, but for driving such of the non-essentials as do not require speed variation it could often be used to advantage. By designing for power factor correction, the voltage variations on the auxiliary bus can be reduced and at the same time increase the power which can be drawn from the auxiliary transformer or generator. The larger motor manufacturers are now building synchronous motors with special clutching arrangements so that the synchronous motor may be used on equipment requiring high starting torque.

Control Considerations

There was a tendency a few years ago to improve the economy of auxiliaries by wide-speed variations and many speed points. Experience has shown that in a number of cases this was carried too far, as the cost and complication overbalanced the economies shown on paper. Today it is realized that it is economically sound to sacrifice some calculated advantages in the interest of simplicity and reliability. The single- or multiple-speed squirrel-cage induction motor is being applied in many cases where previously a wound rotor or d-c. motor would have been used.

Across the line starting eliminates the starting equipment, but where this is used for large motors it may be necessary to provide a means for maintaining the auxiliary bus voltage. When auxiliaries must be started frequently, the manufacturer should be consulted to insure that the oil switches are equal to the unusual duty imposed upon them. Motors also should be built for the heavy duty.

Some engineers look with disfavor on the multiplicity of small oil switches involved with an auxiliary voltage of 2300 or 4000 as these switches require more space than circuit breakers or latched in contactors and are not as readily inspected and serviced. For an installation without excessively long runs and in which the plant expansion is definitely limited, a complete estimate of the probable ultimate can be made with a fair degree of accuracy and the economics as well as the important intangibles studied before reaching a decision on the design. With large motors the copper requirements will be large, but by interleaving the busses and with special transformers, the total voltage drop can be held within practicable limits. Both circuit breakers and contactors are available capable of repeatedly interrupting currents up to 20,000 amperes at 440 volts.

The engineer has the choice of a-c. solenoid contactors operated either by a-c. or d-c. control circuits. If the d-c. control is used it has the advantage of being unaffected by fluctuations of the a-c. voltage, it is quiet,

and the solenoid currents are not affected by the magnetic conditions. For some installations these advantages more than compensate for the added complication of the separate control circuit.

Operating engineers are not agreed on the question of overload protection for auxiliaries. The type of protection depends somewhat upon the installation. In a plant with the essentials in more than one unit, overload relays that will protect the auxiliaries without causing a shutdown of the main unit are a logical arrangement. Where the plant requires operators for the auxiliaries, the overloads have been set at stalled motor current, and in the event of overload the motors are allowed to run hot until the trouble is remedied by the operator.

Completely centralized control and control at the auxiliaries have their applications, the former being somewhat more costly for the equipment and installation. Control at the machine makes it necessary to have additional personnel but in a large plant it is essential that the machinery be regularly examined, and generally these men are available for operating the controls. Control adjacent to the motor reduces the possibility of starting a machine with men working on it and has the important advantage that the operator starting up can see the apparatus and assure himself that it is functioning satisfactorily.

A study of the present station records shows an increasing number of kilowatt-hours sent out per man and an increasing use of automatic combustion and boiler feed control. Some of the combustion control equipment has required a large number of speed points which has made the first cost of the control and motors run high. Multispeed squirrel-cage windings, with fine adjustment on the dampers, will provide a simpler and cheaper solution, and in many cases can be designed so that there is little sacrifice in economy over the operating range. Boiler feed pumps do not involve any special problems other than the multiplicity of speed points which some of the control systems require. Usually, the speed range is relatively small on account of the inherent characteristics of a centrifugal pump and the necessity to keep the discharge pressure at all times in excess of the normal operating pressure of the boiler. The advent of boiler pressure of 1200 lb. and above has resulted in the development of the 3600-rev. per min. wound rotor motor for driving the high-pressure pumps. The design and application of these pumping sets have introduced new problems of control and reliability.

On account of the fire and explosion hazard, pulverized fuel installations should be designed to eliminate the possibility of sparking of control devices or motors in a dusty atmosphere. Good housekeeping is one of the best safeguards. The National Board of Fire Underwriters' rules for pulverized fuel installations provide reasonable safeguards for both the personnel and apparatus.

Report of Subcommittee on Interconnection

Effect of Interconnection on Power Generation.

Interconnection has permitted the size of generating units to be greatly increased so that units of 100,000 or 150,000 kw. are becoming common, while even larger units are under construction. In most of the instances where such large units are being placed in service, they are for the principal use of one operating company rather than for the joint use of parties to an interconnection. However, the individual companies are in reality composed of a number of smaller companies which had previously been interconnected. Interconnection of companies has permitted the total reserve of the district to be decreased since the individual parties need not independently provide for their own emergency. The increased size of units results in a decreased investment per kilowatt of capacity, while the reduced district kilowatt capacity still further reduces the investment in power generation apparatus. Another feature which makes possible the installation of large sized units is the fact that interconnection permits a staggered construction program, so that one company can make a larger addition than it would be justified in making alone, and its investment charges can in part be carried by the other interconnected companies.

The consumption of fuel is reduced because of the possibility of giving the more economical units the "base load" of an entire district and because water power can be used more effectively. There is a number of examples where the power which could be developed from stream flow plants during certain hours of the day was wasted and is now used due to the interconnection of systems which gives a greater outlet for the energy.

Reasons for Interconnection.

By far the largest number of interconnections has been of the type where small systems have been merged financially with larger systems, and the natural tendency was to abandon the smaller of the generating stations and interconnect the systems. Much of this has been done without detailed studies as to the possible economy, the problem being considered in the light of the consolidation of property.

However, there is also a number of interconnections between large systems having separate management. These interconnections are made for one or more of the following reasons of economy or improved reliability of service:

(a) Generating reserve; (b) load diversity; (c) mutual assistance during emergency; (d) minimizing possibility of territorial power shortages; (e) utilization of water power; (f) additional business due to coverage of intervening areas.

The primary object of interconnections in the final analysis is of course a reduction in investment and

operating cost. Presumably, it is possible to build and operate an independent system which will give the equivalent of a system interconnected with others, but interconnection affords a more economic method of accomplishing the desired results.

Methods of Interconnecting.

Of the two methods of interconnection, namely, loose and tight linking, no conclusive arguments in favor of one or the other appear to be generally applicable. The distinction at the present time seems to be principally that of purpose. Where loose linking is in operation, the primary object is to provide facilities for the interchange of power for known requirements, and where a certain amount of time can be allowed for connections. In this case, the member systems of an interconnection are each capable of providing for their own requirement, with the exception that provision is made for the actual transfer of load by switching to take care of inequalities between the load and available generating capacity. Thus to a certain extent all of the possible benefits of interconnection are not realized, but on the other hand, some of the complications are avoided. Where tight linking and trunkline ties are employed, the facilities of the group are at all times available to each of the member systems. The complication and expense of the interconnecting ties, however, are greater for this condition.

Problems of Interconnection.

The principal technical problems at the present time appear to be in connection with the following subjects:

(a) Load control; (b) load dispatching; (c) voltage control; (d) frequency control; (e) relaying; (f) stability; (g) increased short circuit currents and adequacy of circuit breakers and other equipment; (h) communication; (i) metering; (j) technical basis of contractual relations.

Several of the items given above are not peculiar to interconnection but appear in the planning of any system, and improvements are continually in progress, applying equally well to system and interconnection design.

There is an increasing tendency toward the use of automatic recording devices for filling the gaps between the information from station operators and what is left of a system after a disturbance; and it is highly probable that when accurate information from these devices on systems throughout the country over a period of time is available, some very constructive new ideas will result.

Report of Subcommittee on Hazards to Service Reliability in Modern Generating Stations

This subcommittee has endeavored to obtain discussion by designers and operators of generating plants regarding the major hazards that have developed to station capacity as the result of recent trends in the

design features of modern power generating stations. Modern stations are characterized in the main by magnitude of total capacity and by concentration of capacity in individual machines, both electric and steam generators. These tendencies apparently have not brought to light any new types of hazards, but have rather accentuated possibilities of service interruption that had already been experienced or predicted. In some types of older plants severe interruptions have occurred recently, as the result of inadequate or faulty design of an earlier date. While the subcommittee recognizes that an accident hazard to operating personnel may develop into a major capacity outage, or vice versa, it has not been directly interested in this phase of station reliability, realizing that such viewpoints are being thoroughly treated by the Accident Prevention Committee of the National Electric Light Association, and by other N. E. L. A. committees dealing with particular machinery applications. Other national organizations, such as the American Society of Mechanical Engineers and the National Safety Council, have devised safety codes covering practically every aspect of power plant operation.

Capacity Hazards in Hydroelectric Generating Plants.

There are undoubtedly quite a few plants in use that suffer severe capacity reductions from ice, trash, and occasional failure of auxiliary control, but for all practical purposes these problems may be regarded as solved in the large capacity hydro stations of modern design.

The subcommittee has received notice of some recent failures of high head penstocks that were designed and constructed some years ago. The remedy suggested has been to have some automatic means, independent of electrical or manual control, of shutting off the water supply in case of such a failure. This has been done by installing valves at the head of important penstocks which are capable of operation against full unbalanced pressure and which are arranged to close automatically with suitable time interval in case the water velocity increases above a predetermined value. These valves may also be closed from the power house, but it is necessary for the attendant to be at the valve in order to open it.

An operating hazard that seems to have been of increasing aggravation is over-voltage upon sudden loss of load. This has been intensified in cases by the use of quick response excitation and high transmission line voltages. The remedy seems to have been additional overvoltage relays to control the voltage regulators as necessary, supplemented in some instances by special governor adjustments.

Capacity Hazards in Steam-Electric Generating Stations.

Some operators, as well as designers, have objected to the increasing complexity of electrical control of the auxiliaries in steam stations, particularly those employing the newer systems of boiler plant combustion.

The multiplication of automatic safeguards and devices has also been condemned as defeating the purpose for which they were installed.

Engineers who are installing the extra large boilers and turbines expect a minimum outage from the troubles that have been bothersome in the past, such as winding failures, blade breakage, and refractory and tube replacements. Engineers operating cross-compound turbine units have expressed the opinion that outage of one element practically means the outage of the entire unit. There seems to be a slight betterment of operating availability of boilers and turbines, but blade failures and winding burnouts still continue to be reported, notwithstanding the intensive research and improvement that has been accomplished in the selection and fabrication of materials.

Particular Electrical Hazards.

The fire hazard in the operation of modern power systems still seems to be one that deserves considerable thought. Fires resulting from the failure of oil filled equipment, such as oil circuit breakers, regulators, and transformers, with the resulting spread of oil throughout the station, are probably the most common and the most serious hazard, judging from the reports from the various operating companies. It seems that fires of this nature have in many cases resulted from the breaking of oil gages in oil filled equipment, permitting the escape of oil in the station to other apparatus and in turn breaking oil gages on that equipment and so on until serious fires have resulted. The solution so far has been the application of ball check valves to back up the oil gages and to design the station so that escaping oil is confined locally. It seems that serious consideration should be given to the perfection of an unbreakable oil gage.

The oil circuit breaker problem, while of considerable standing, is being constantly presented by the growth of interconnected capacity. Serious damage is reported in switch houses due to the spreading of vapors arising from short circuits and faults to ground. In some cases the solution of this problem has been the complete insulation of the busses; in some other instances firewalls have been installed; but in most cases the spreading of such vapors is minimized by cutting out the faulty section of the bus as quickly as possible after the fault develops, by a proper relay system.

One of the greatest hazards in a generating station is that of a bus short circuit and the resulting effects on system stability. A bus short circuit in a generating station usually requires the unloading and the resynchronizing of those generators connected to the faulty bus. If system stability is to be insured at all times, the following requirements must be met:

1. Each generator must be normally connected to at least two separately insulated busses.
2. The total reactance in series with the generators must be low for normal current flow in order to insure good voltage regulation.

3. The reactance, including that of the generator, between each generator and a short circuited bus must be on the order of 60 per cent if the generators are to maintain a substantial voltage on the non-short-circuited bus.

4. A short circuit on one bus should result in a tendency of the generators to raise the voltage an amount sufficient to compensate for the voltage drop produced in the generators by the short circuit.

A method has been proposed in which each generator is connected to two separately insulated high-voltage busses through a transformer having two separately insulated high-voltage windings. Such a transformer would be similar to the 83,333-kv-a. transformer on the system of the Buffalo General Electric Company. The transformer for the proposed scheme would be designed to have an impedance from the primary to one secondary winding of approximately 50 per cent, and from the primary to the two secondary windings, feeding balanced load, of approximately 15 per cent. Such a transformer, when operating with a generator adapted to feed a maximum current of 150 per cent at 75 per cent voltage, will automatically step the voltage to zero on the short-circuited bus and to 105 per cent on the non-short-circuited bus. If the maximum permissible instantaneous short circuit that can be permitted to flow from the generators to one bus is limited to 1,500,000 kv-a., then with a total normal reactance, including 10 per cent generator reactance, between the generator and the high-tension bus of 25 per cent, the maximum generator capacity that can be connected to a single bus is 375,000 kv-a. On the other hand, if the double-wound secondary transformer with a total reactance of 60 per cent to a short circuit on either bus (including 10 per cent generator reactance) is used, then 900,000-kv-a. capacity may be tied to a single bus, and either one of such a pair of busses may be short-circuited with practically no danger of any machine pulling out of step. This is probably as great a capacity as will be concentrated in any one station for some years to come.

It is obvious that if an ultimate station capacity, greater than 900,000 kv-a. is expected, three such busses could be used and three such secondary transformer windings, each corresponding secondary winding in each transformer bank being connected to one of the three busses.

Other methods of enhancing system stability in case of trouble include the paralleling of generator groups at a distance from the generating station, and the use of two winding generators whose windings are connected to bus sections separated by proper reactance.

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- 5 d—Electrical Power Plants
- 7 b—Heat Power Boilers
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 - f—Steam Power Machinery
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Discussion

P. B. Junke: How long will the present growth of systems continue? During the last twenty years, the systems have been about multiplied by eleven. If the same growth continues in the next ten years, we shall have quantities to deal with that perhaps few of us give consideration to at the present time.

In Chicago, whereas at the present time we have a system total of about 1,400,000 kw., by 1940 the estimated load will be on the order of 4,000,000 kw.

Another topic that needs discussion is the subject of rehabilitation of plant. In our system we have old plants to the extent of about 300,000 kw., and quite often the thought has been suggested to rehabilitate these. If we look at our composite load curve, we find that this old capacity, written off for all practical purposes, serves a very useful function. It carries the peak load of the system quite nicely for a period of about three or four hundred hours a year. That is perhaps the best function it can perform and the capacity in that form is perhaps the cheapest that can be obtained for that purpose.

In the report a suggestion is made that new plants be built for peak purposes at rather low cost. Where you have old capacity available for such a purpose, I think that is the very cheapest kind of capacity to be preserved for such a function.

One other subject dealt with in the paper entitled *Synchronized at the Load*, must be given thorough consideration, that is, the splitting up of certain systems into sections relatively safe under all conditions. I would suggest that this topic be given additional study and consideration as one of the outstanding problems.

Transmission and Distribution

ANNUAL REPORT OF COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION*

To the Board of Directors:

The work of the Committee on Power Transmission and Distribution covers a wide field and may logically be divided into the following classifications:

- Lightning and surge problems on overhead lines
- Insulator design for overhead lines
- Design of towers and poles for overhead systems
- Cable development for underground systems
- System connections and stability factors
- Standardization activity
- Research activity.

The work carried on this year has been confined to the lightning and insulator problems handled by a subcommittee under the leadership of Mr. Sporn, cable development handled by a subcommittee under the direction of Mr. Peterson, and system connections and stability factors handled by a subcommittee under the direction of Mr. Evans, with Mr. Farmer coordinating the standardization activities and the research work carried on under the direction of a joint research committee working under the auspices of the N. E. L. A. Underground Systems Committee, Association of Edison Illuminating Companies' Committee on High Tension Cable, and the Power Transmission and Distribution Committee of the A. I. E. E.

The problems arising under the above activities are so closely related with similar problems handled by other committees of the Institute and other organizations that considerable attention has been given to coordinating this work so as to eliminate unnecessary duplication and at the same time insure the proper handling of all subjects. In light of this condition, your committee has not initiated any work on inductive coordination and any consideration of the interference aspect of such subjects is being tied in with the work of the Joint General Committee and the activity of the work on stability factors and interconnection has been referred to the Committee on Coordination of Institute Activities for assistance in subdividing this work between the various committees.

*COMMITTEE ON POWER TRANSMISSION AND DISTRIBUTION:

H. R. Woodrow, Chairman,	E. W. Dillard,	E. R. Northmore,
R. E. Argersinger,	R. E. Doherty,	L. L. Perry,
Geo. M. Armbrust,	L. L. Elden,	T. F. Peterson,
R. W. Atkinson,	R. D. Evans,	D. W. Roper,
E. T. J. Brandon,	F. M. Farmer,	A. E. Silver,
V. Bush,	Harland C. Forbes,	L. G. Smith,
P. H. Chase,	O. L. Fortescue,	H. C. Sutton,
C. V. Christie,	K. A. Hawley,	Percy H. Thomas,
D. D. Clarke,	V. L. Hollister,	Philip Torchio,
W. H. Cole,	J. P. Jollyman,	Theodore Varney,
R. N. Conwell,	A. H. Kehoe,	H. L. Wallau,
M. T. Crawford,	A. H. Lawton,	H. S. Warren,
W. A. Del Mar,	W. E. Mitchell,	R. J. C. Wood.
Herbert H. Dewey,		

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

A summary of the developments and problems arising during the year is covered in the following reports from the subcommittees:

SUBCOMMITTEE ON LIGHTNING AND INSULATORS

PHILIP SPORN, CHAIRMAN

GENERAL ASPECTS OF THE LIGHTNING PROBLEM

Lightning disturbances on electric circuits have always been a problem; the importance of these disturbances becomes greater with the increase of interconnecting high-voltage lines, transmitting large blocks of power, which now form the backbone of interconnection and in many cases the basis of economic generation. The transmission line, therefore, becomes a vital link in the electric circuit; and lightning, by its adverse effect on its operation, its worst enemy. The demand for more reliable line operation, from a lightning standpoint, has started investigation and research, beginning with isolated field investigations with crude and limited instruments, next laboratory research with the lightning generator, and then to field investigation with the klydonograph and surge recorder, and finally to the cathode ray oscillograph in both the laboratory and field.

Both the laboratory and field have contributed to the solution of the lightning problem. The laboratory by offering complete and easy control of the lightning wave has, of course, rendered investigations far more simple than field research.

Theory, too, has contributed its part in studying the mechanism of cloud formation and lightning discharges, the breakdown of the discharge path, the influence of ground wires, the characteristics of the electrostatic field, the effect of traveling waves on electric circuits, and the shape and effect of different shapes of traveling waves on the insulation strength of the line and the connected apparatus. A noteworthy contribution to the study by the field is the record of lightning disturbances and trouble on lines as encountered in actual service, together with complete storm data where available.

Finally, an extension of the development has been made in combining the laboratory and field in the form of artificially created lightning imposed on actual transmission lines. Certain problems that prove difficult of solution, such as wave propagation, can best be handled that way.

With this background it is clear the solution of the lightning problem has received progression acceleration the past few years, and a large amount of lightning

data has been secured and many of the results published in the technical press. Even with considerable theoretical analysis, and with laboratory and field data available, the lightning problem is not solved. Some phases of lightning are only partly known; others are in dispute; and some are definitely not known.

COMMITTEE PROGRAM PLANNED

One of the undertakings of the committee is to outline what is definitely known about lightning as affecting electric circuits, and include in this subject important factors on which there is general agreement. On phases of the problem where there is disagreement, it is hoped and expected a thorough discussion and analysis will produce an agreement on most if not all disputed points. Where investigations are carried on independently and without coordination, it is to be expected different conclusions may be drawn. Perhaps it is well this should initially be so, since coordination, when a problem is first attacked, might stifle original ideas and tend to place the whole investigation in a rut. It is believed, however, that in the case of the lightning problem, this stage has passed, and that there is room now for reaching a definite understanding on many phases of the work. Such an understanding, it is believed, will be of great value to all investigators, manufacturers, and utility engineers and operators.

With past lightning data and theories correlated, as above outlined, it should be possible to state clearly what additional information is needed, and to indicate what is most urgently needed. The committee plans to do this.

The past lightning investigation work in the field has been done on the higher voltage circuits, largely, as previously pointed out, due to their importance in the electrical network. However, it is felt desirable to apply the information already secured to the lower voltage systems, and even to the distribution networks. A general survey of both transmission and distribution systems is planned to determine how lightning affects both. This requires analysis from theoretical, operating, and the economic points of view.

The lightning problem on electric circuits is primarily an insulation problem, and consequently requires not only a study of voltages which may occur, and the nature of those voltages, but also the distribution of insulation in the apparatus and on the electric system to prevent any electric breakdown if possible, but in any case to localize trouble at a predetermined and least damaging point. This at once requires a broad consideration of the insulation of the lines and connected apparatus as related to each other.

Remedial measures against lightning and beneficial accessories where power arcs follow up will require thorough analysis supported by operating experience. These include lightning arresters, ground wires, grading shields, insulated ground wires, protective gaps, insulation of wood poles and crossarms, insulated guy wires, fused arcing rings, etc. Here too, a balance is

required between the beneficial effects expected, or proved to exist and increase in reliability of service and cost.

LIGHTNING PROGRESS DURING 1928

During the past year some dozen field investigations have been in progress by the operating companies in cooperation, in most cases, with the manufacturers. Many data have been added to our present store regarding the magnitude of lightning voltages on transmission lines, attenuation of this voltage, and characteristics of traveling waves. Three cathode ray oscillographs have been in operation during part of the 1928 lightning season, and two photographs of actual lightning voltage recorded. While many more data are needed on lightning wave characteristics, this is a noteworthy beginning.

A method of attacking the lightning problem, as mentioned above, has been put into use again in the past year. This consists of placing artificial lightning surges on actual transmission lines and observing with the cathode ray oscillograph the behavior of the wave at short-circuited and open-circuited points on the line, and further determining attenuation of the wave. This investigation has been very useful in studying the behavior of the lightning wave, and promises much for the future.

The past year has seen the continuation of ground wires being used on new lines, and their addition to some existing lines. The grading shields on insulator strings, extensively used in the past few years, have been in many cases installed on new lines. The practice of reducing the line insulation for a mile or so out from the substation, to protect station equipment from lightning, has been extended. Additional (more than one—in some cases three total) ground wires have been installed from the substation out for the first two towers or so on the line, to reduce the line surge impedance, and as a further protection against direct strokes. In some cases these additional ground wires have been carried on separate structures.

RESEARCH WORK IN PROGRESS

Surge investigation installations are in progress on the transmission lines of a number of operating companies. Some ten or twelve cathode ray oscillographs are planned to be in operation on actual lines during the summer of 1929 to record lightning waves. Two or more additional installations to record the performance of artificial lightning are also planned for this summer. It can be seen that quite an extensive program has been planned; and it is expected effective work will be accomplished.

The great number of papers and articles which appeared during the past year on lightning and related subjects affecting the transmission system from the lightning point of view, clearly indicates the growing importance of the lightning problem. They further show the many angles of attack from which investi-

gators are working. A list of the more important papers and articles, which have come to the committee's attention, is given below.

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2. Power Transmission and Distribution, Concluding Report of the 1927-1928 Sub-Committee, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 487.
3. *A Graphical Theory of Traveling Electric Waves*, by V. Karapetoff, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 508.
4. *Progress in Lightning Research in the Field and Laboratory*, by F. W. Peek, Jr., A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 436.
5. *1927 Lightning Experience on 132-Kv. Transmission Lines*, by Philip Sporn, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 480.
6. *Theoretical and Field Investigation of Lightning*, by C. L. Fortescue, A. L. Atherton, and J. H. Cox, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 449.
7. *Electric Oscillations in the Double Circuit 3-Phase Transmission Line*, by Y. Satoh, A. I. E. E. Quarterly TRANS., Vol. 47, Jan. 1928, p. 58.
8. *Surge Impulse Breakdown of Air*, by J. J. Torok, A. I. E. E. Quarterly TRANS., Vol. 47, April 1928, p. 349.
9. *The Cathode Oscillograph as Used in the Study of Lightning, etc.*, by Harald Norinder, A. I. E. E. Quarterly TRANS., Vol. 47, April 1928, p. 446.
10. *1926 Lightning Experience on 132-Kv. Transmission Lines*, by Philip Sporn, A. I. E. E. Quarterly TRANS., Vol. 47, April 1928, p. 668.
11. *Relation between Transmission Line Insulation and Transformer Insulation*, by W. W. Lewis, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 987.
12. *Rationalization of Transmission System Insulation Strength*, by Philip Sporn, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 998.
13. *Surge Voltage Investigation on Transmission Lines*, by W. W. Lewis, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1111.
14. *Lightning Investigation on New England Power Company's System*, by E. W. Dillard, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1122.
15. *Surge Voltage Investigation on the 140-Kv. System of the Consumers Power Company during 1927*, by J. G. Hemstreet and J. R. Eaton, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1125.
16. *Surge Voltage Investigation on the 132-Kv. Transmission Lines of the American Gas and Electric Company*, by Philip Sporn, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1132.
17. *Surge Voltage Investigation on 220-Kv. System of Pennsylvania Power and Light Company*, by N. N. Smeloff, A. I. E. E. Quarterly TRANS., Vol. 47, October 1928, p. 1140.
18. *Lightning Arrester Problems*, by A. L. Atherton, A. I. E. E. Quarterly TRANS., Vol. 48, January 1929, p. 141.
19. *High-Voltage Phenomena in Thunderstorms*, by M. A. Lissman, A. I. E. E. Quarterly TRANS., Vol. 48, January 1929, p. 146.
20. *Impulse Flashover of Insulators*, by J. J. Torok and W. Ramberg, A. I. E. E. Quarterly TRANS., Vol. 48, January 1929, p. 239.
21. "Plans for Lightning Tests," by A. L. Atherton, *Elec. World*, July 1928, p. 165.
22. "Effect of Ground Wires on Traveling Waves," by J. H. Cox and J. Slepian, *Elec. World*, September 1928, p. 551.

23. "A Theory of Lightning," by C. L. Fortescue, *Elec. Jl.*, May 1928, p. 221.

24. "Some Electrophysical Conditions determining Lightning Surges," by Harald Norinder, *Franklin Inst. Jl.*, June 1928, p. 747.

25. *A New Type of Hot Cathode Oscillograph and its Application to Automatic Recording of Lightning and Switching Surges*, by R. H. George, A. I. E. E. Quarterly TRANS., Vol. 48, July 1929.

26. *Investigation of Transmission Lines with Artificial Lightning*, by K. B. McEachron, A. I. E. E. Quarterly TRANS., Vol. 48, July 1929.

SUBCOMMITTEE ON CABLE DEVELOPMENT

T. F. PETERSON, CHAIRMAN

GENERAL STATEMENT

The portion of last year's Power Transmission and Distribution Committee Report dealing with cable developments included descriptions of what might be considered remarkable advances and great strides in the transmission art. Of these, the design, installation, and operation of 132-kv. oil-filled cable were most notable. This year nothing so sensational is to be noted. Practically all development and improvement seem to have been characterized by a tendency toward review and analysis of existing practises, stabilization, and reduction of known methods and principles to economic and practical feasibility. These have apparently constituted the bases for such crucial investigations of paper insulated cable of the so-called solid type, sheath corrosion, sheath current mitigation, temperatures of conduits, etc., as have been reported in the technical press throughout the year. The splendid cooperation and coordination of results evidenced by various organizations, utilities, and manufacturers engaged in the improvement of cable bids fair toward hastening the day of our profound understanding of cable and its operation.

RESEARCH

Though the research may not, of itself, constitute development (taking this in the sense of completion), experience has indicated that it undoubtedly frames the potentialities for development. It is probably not generally appreciated how much research work on high-tension cable is now being done. The annual report of the Impregnated Paper-Insulated Cable Research Subcommittee (this is a joint subcommittee of the Underground Systems Committee, N. E. L. A., the High Tension Cable Committee, A. E. I. C., and the Power Transmission and Distribution Committee, A. I. E. E.) gives a comprehensive picture of the extent of these activities in the industry, from which it is evident that expenditures on research have been greatly increased in recent years. A significant feature in this connection is the cooperative spirit displayed in the industry. Much work is being done directly under cooperative auspices but even that which is done under private auspices is reported freely to the industry. This augurs well for the development of the art to the mutual

advantage of all concerned,—central station companies, manufacturers, and the public.

Accomplishments to date have been variously reported to the A. I. E. E. and A. E. I. C. The annual report of the aforementioned joint subcommittee includes a résumé of all activities.

At Massachusetts Institute of Technology, under the direction of Professor Bush, there has been concluded an extensive investigation of the rate of deterioration of wood pulp paper for cable insulation when subjected to heat alone. The final conclusions reached are to the effect that impregnated wood pulp paper now being used in cables will withstand a temperature at least as high as that which manilla paper will withstand and, in so far as the rate of deterioration of the paper itself is concerned, the permissible operating temperatures of high-tension cable could be considerably higher than those now prescribed.

At Johns Hopkins University, the study of the effects of residual air and moisture in the insulation is progressing. Results already available point to the relative unimportance of extremely low air pressure of impregnation for obtaining excellent power factor—voltage curves. It appears that difficulties with commercial cables are due very largely to extended areas of entrapped air and gases resulting from imperfect impregnation, distortion in handling, or expansion of the lead sheath.

The study of the laws governing ionization characteristics of cable insulation has progressed at Harvard University to the point where simple empirical equations have been established for the experimental curves obtained.

The work at these and other universities has been closely followed and supplemented by individual researches conducted by various manufacturers and central station companies. At Brooklyn, accelerated life tests on cable, studies of the stability of impregnating compounds, and the ultimate nature of breakdown of gaseous spaces comprise some of the problems receiving attention. The research staff of the Detroit Edison Company has made extended laboratory and field tests of insulation of the solid type. These have included the study of the rate of oil absorption, gas generation, and change of power factor of cables in service, as well as investigations of hydrostatic pressure variation with temperature of cable and the development of a suitable laboratory test which will make cable deteriorate in the same manner in which it does in service. The Commonwealth Edison Company, through the Utilities Research Commission, is conducting elaborate theoretical studies of the fundamental nature of insulation as, for example, the significance of the dielectric strength of insulation, by Professor Compton at the University of Chicago, the determination of the relation of dielectric absorption and dielectric losses by Professor Whitehead at Johns Hopkins, and the study of the physical properties of ordinary cable

lead sheaths by Professor Moore at Illinois. In addition to this, they have contributed much of a more or less practical nature.

DEVELOPMENTS IN PRACTISE

In last year's report mention was made of the placing in service of 18 miles of 132-kv. lines in Chicago and New York. It is worthy of note that these lines have continued to operate up to the present date without electrical failures. An additional 12 miles of circuit at 132-kv. is now being installed in New York, the cable being of the hollow core, oil-filled type, in general similar to that in use on the previous lines. An important advancement in the method of installation has been made in that it is now possible to install the cable filled with oil, thereby eliminating the field impregnation which was required on the first circuits.

The several installations throughout the country of 45-kv. and 66-kv. single-conductor cables of the solid insulation type have continued to give satisfactory service. The use of oil reservoirs on the joints has proved very beneficial as far as the joints are concerned and thus far the possible trouble which some engineers have feared from the expansion of the cable sheaths has not been manifested.

During the past year, a pioneer installation of three-conductor oil-filled cable has been made in Chicago. This particular circuit was designed for 33-kv. operation but it is expected that cables of similar construction can be built for voltages up to 66 kv. The possibility of reducing the thickness of the insulation by means of the oil-filled construction apparently will make it feasible to increase the amount of power which can be transmitted through a duct and it is quite probable that if this development gives satisfactory operating results, there will be a considerable trend toward the use of three-conductor cables in the range of 33 to 66 kv. The improved regulation of three-conductor cables and the elimination of sheath losses are other features which make this type of construction appear attractive as compared to single-conductor cables. The shielded or Hochstadter type of construction continues to find favor for three-conductor cables designed for working voltages in the range of 22 to 33 kv.

For the lower voltages, including cables operating at voltages between 11 kv. and 15 kv., three-conductor cables and single-conductor cables installed three per duct have been used more or less indiscriminately, advantages being claimed for both. With the prospect that cables of this class will be used rather extensively in the future as a primary supply to a-c. low-voltage networks, the question of regulation has become of considerable importance and the superior characteristics, in this respect, of three-conductor cables, may henceforth carry considerable weight.

Notwithstanding this trend, there have been presented several papers (referred to elsewhere) embodying in a very tangible way economic studies of sheath cur-

rent elimination in single-conductor cables and losses in armored single-conductor cable. These, coupled with the development of new types of insulating sleeves, the *H* and *N* sheath bonding transformer and similar equipment, is evidence of the widespread interest in this field.

It has long been felt that our present method of rating cables, based on temperature limit of insulation, was, to say the least, unsound. The lack of a suitable alternative has accounted for the retention of the present method. As an example of the coordination of effort referred to heretofore, we point to a structure of understanding which is being built up to alter these conditions. The work at M. I. T. has definitely established the fact that, based on deterioration due solely to temperature, cable may be operated at considerably higher values than at present. It is recognized, however, that other factors enter which are the controlling ones. At Chicago and Detroit, systematic studies of the performance of cable fitted with oil-filled joints and under cyclic loading have been under way. At the former place, numerous tests have been made to determine the effect of various manhole designs on the ability of cable sheath to withstand the expansion and contraction incidental to normal operation. The Electrical Testing Laboratories and others are adding to our information by making like tests under repeated loadings. In other quarters, very extensive surveys of conduit and soil temperatures have been made and methods have been evolved for the determination of cable temperature when the loading and ambient conditions are known. It is evident that, with such a mass of data becoming available, we should, before long, be in a position to set up a rational method of rating cable.

During the past year, considerable interest has been exhibited in sheath corrosion. Several companies have observed the formation on lead sheath of various red, orange, and white compounds. Inasmuch as these, especially the red lead oxide, made their appearance on cable installed in monolithic concrete duct which was coming into very general use, they gave rise to considerable alarm among those operating and extending such systems. Almost coincidentally, there was reported considerable corrosion of lead sheath in creosoted wood ducts.

These apparently baffling problems were the subject of attention of the Utilities, N. E. L. A., and the Portland Cement Association. Through their concerted effort, the contributing factors were soon laid bare and palliative measures were introduced, with the result that, at the present time, little fear is felt for troubles of the type mentioned. In the case of the concrete duct, it appears that the presence of calcium hydroxide from the concrete, water, and a-c. electrolysis or slowly reversing currents conspire to produce the oxide. Elimination of water and electrolysis would undoubtedly prevent the formation. In addition, if the

concrete is allowed to stand for approximately 28 days, during which time the calcium hydroxide is changed to calcium carbonate, and if the concrete is sufficiently dense to prevent water from permeating it and dissolving additional calcium hydroxide, cables should be relatively free from corrosion of this type.

Corrosion in wood ducts was found to be due to the attack of the lead by acetic acid, of which there was considerable amount evolved from the Douglas fir used for the conduit. The remedial measure applied in this case was to introduce ammonia gas into the duct, thus neutralizing the acid.

SPECIFICATIONS, TESTING, AND OPERATION OF CABLE

There has been no important change in cable inspection and testing practice during the year. Specifications remain practically unchanged except for an increase in test voltages for single-conductor and shielded type multiple conductor cables, as well as a decrease in the allowable ionization factor in high-voltage cables. As in previous years, a survey of the test results obtained shows a general trend in the direction of improvement. This is indicated by the percentage of deficiencies and the uniformity of insulation resistance, power factor, and ionization factor. This consistent trend toward improvement is now being reflected in decidedly better operation of cable as revealed in annual reports of operation which have been compiled. Analytical studies of the mass of data that are collected annually in connection with acceptance inspection and testing of cable and of failures of cable which occur in service, have been carried on for several years. The value of these studies as an aid in improving cable having been demonstrated, more effective means of carrying them on has been developed under the cooperative auspices of the National Electric Light Association and the Association of Edison Illuminating Companies. This development is another indication of the cooperation which exists in the industry and which cannot help but be a great aid to progress.

The need for this progress is quite evident when cognizance is taken of the fact that it is generally conceded that, even with the multiplicity of tests which we now apply, we have no means of predicting with certainty whether cable will give satisfactory service and we have nothing which is a final measure of cable quality. However, with such concerted effort and cooperative action as have been described throughout this report, there is every reason to believe that this condition will not obtain for any great length of time.

TECHNICAL PAPERS ON RELATED SUBJECTS

This report is essentially a résumé of subjects covered in such papers as the following:

- Bailey, *Heat Flow from Underground Electric Power Cables*, A. I. E. E. Quarterly TRANS., Vol. 48, Jan. 1929, p. 156.
 BURNS and FREED, *Corrosion of Cable Sheath in Creosoted Wood Conduits*, A. I. E. E. Quarterly TRANS., Vol. 48, Jan. 1929, p. 166.

SHANKLIN and MACKAY, *High-Tension Underground Cable Research and Development*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 338.

DAVIS and EDDY, *Some Problems in High-Voltage Cable Development*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 373.

DAWES, REICHARD, and HUMPHRIES, *Ionization Studies in Paper-Insulated Cables*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 382.

HALPERIN and MILLER, *Reduction of Sheath Losses in Single-Conductor Cables*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 399.

SCHURIG, KUEHNI, and BULLER, *Losses in Armored Single-Conductor Lead-Covered Cable*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 417.

WHITEHEAD and MARVIN, *Anomalous Conduction as a Cause of Dielectric Absorption*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 299.

KITCHIN, *Power Factor and Dielectric Constant in Viscous Liquid Dielectric*, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 495.

Publications of N. E. L. A. and Reports of A. E. I. C. for year 1928.

STANDARDIZATION ACTIVITY

F. M. FARMER, CHAIRMAN

The following is a brief summary of standardization activities which have been consummated during the year.

1. Section No. 30 of the Standards of the A. I. E. E. dealing with wires and cables has been submitted to the American Standards Association for ratification as an American Standard (minus certain items which are now under discussion).

2. Specifications for annealed copper wire both bare and tinned were approved as American Standard by the American Standards Association, June 12, 1928.

3. Specifications for 30 per cent rubber insulation for wire and cable for general purposes were approved by the American Standards Association as tentative American Standard, April 2, 1928.

4. Specifications for magnet wire were approved by the American Standards Association as tentative American Standard, April 2, 1928.

A number of matters dealing with wires and cables is in the course of development to the standardization stage. Specifications for impregnated paper insulation, specifications for varnished cloth insulation, and specifications for weatherproof heat resisting and other coverings are being developed by the Sectional Committee on Wires and Cables of the American Standards Association. Similarly, progress is being made with the development of a standard stranding table for stranded conductors by the same committee.

Informal arrangements have been made between the appropriate committees of the National Electric Light Association and the Association of Edison Illuminating Companies for the coordinated collection and study of cable failures on a standardized basis.

SUBCOMMITTEE ON INTERCONNECTION AND STABILITY FACTORS

R. D. EVANS, CHAIRMAN

Interconnection of power systems has been brought about as a natural result of consolidation under a common management or as a measure to reduce investment or operating expense of systems under separate managements. The general advantages, such as those arising from load diversity, generating reserve, and utilization of stream flow plants, have been recognized for some time. The problems at hand have to do with the determination of the economy of a particular undertaking and the selection of the best method of carrying out the interconnection.

One of the most important aspects is the reliability of the power supply obtained from the interconnection. Reliability depends to a large extent on the vulnerability of the system and the stability of the system, *i. e.*, its capacity to maintain the machines in synchronism at times of system disturbances. These problems are very prominent in the field of power transmission, as the means of interconnection consist of transmission lines or ties with the associated transformers and switching equipment, and as the location, number, and character of these ties largely determine the serviceability of the interconnection.

The study of system connections is a development whose importance has recently become generally recognized. While it is true that different power system connections have developed in different parts of the country, these differences could largely be explained because of the difference in the local situation as to the transmission distance, the density, and the distribution of the load. Increase in the extent of systems and of interconnection has made it necessary to give consideration to what are commonly called "System Problems," of which stability may be cited as an example. Stability was first carefully analyzed in connection with long-distance power transmission. More recently, these principles are being applied in the study of the closely-connected systems.

The plan of operation of interconnected systems may be premised on either the maintenance of synchronism at times of system disturbances or upon the separation of the systems. In the latter case the system may be split at fixed points or at variable points to coordinate connected load and generating capacity. At the present time it is not possible to draw any general conclusions as to the proper field of application of these different methods of operation.

In the design of systems to maintain stability, several distinct methods are recognizable. Synchronism may be maintained (1) by measures which increase the synchronizing power which may be transferred between the machines, as by the use of low reactance tie lines or the application of quick response excitation; (2) by measures which limit the severity of the shocks to the

system occasioned by faults, as may be affected by the use of individual lines of high reactance or by quicker fault isolation; or (3) by a system layout which causes the shock to be distributed to the various machines in such a way as to accelerate or decelerate them as a unit.

In order to improve stability, special attention is being given to the characteristics of apparatus to be used on extensive systems and interconnections. From the standpoint of stability, governors should operate quickly and should possess anti-hunting features tending to reduce oscillations after disturbances. Governor operation in direct response to fault indications may prove advantageous. Field test to indicate performance of governors under transient conditions would be very desirable.

In generators, high short circuit ratio and low transient reactance are of benefit in improving the power limits. The use of the proper kind of excitation system extends the power limit under both steady state and transient conditions and may largely overcome the disadvantages of low short circuit ratio. Low transient reactance will improve the stability conditions at times of system fault. In general, a study should be made to determine in each case the proper value of machine transient reactance which depends upon line and transformer as well as generator costs.

Consideration is being given to the use of damper windings in waterwheel generators. Damper windings tend to improve stability by virtue of their damping action and to decrease stability because of the increase in fault current due to the reduction in negative phase sequence reactance of the generator. Investigations have indicated that in certain cases damper windings may be advantageous provided they are of the proper characteristics.

Excitation systems capable of quick response are effective in improving stability under steady state and particularly under transient conditions. In special cases the use of synchronous condensers wholly or principally as an aid to stability will be found desirable. The stabilizing effect of such condensers will be increased by the application of suitable quick response excitation systems.

During the past year actual field tests with quick response excitation systems were reported in a paper on *Power Limit Tests* by S. Murray Jones and Robert Treat. A general review of stability was presented by R. H. Park and E. H. Bancker in their paper on *System Stability as a Design Problem*.

The investigations by the Lightning Subcommittee and the Protective Device Committee on protective measures, for minimizing the effects of faults, are very pertinent in consideration of the stability problem. Measures, such as the high insulation of lines and the installation of ground wires, by reducing the number of faults are obviously of benefit from the standpoint of stability. There is a growing tendency to proportion line insulation to service requirements, thus minimiz-

ing the number of faults occurring in exposed areas. Ground wires also tend to reduce the value of the resistance in the ground connection at a flashover point, which may either increase or decrease the resulting shock to the system.

Consideration is being given to power arc suppression devices. Phillip Stewart in his paper on *Fused Arcing Horns and Grading Rings* gave the results of operating experience. During the past year some interest has been shown in the Peterson coil as an arc suppression device.

There is some consideration of the introduction of neutral impedance devices for limiting the shock to the system at times of fault to ground. Of course, these devices are of advantage from the standpoint of stability if they reduce the shock to the system and if they do not at the same time increase apparatus failure or line flash-over or interfere with the prompt isolation of faults.

Consideration is being given actively to the matter of the duration of the short circuit condition as it is clear that the system oscillations are minimized when the fault duration is reduced. From this standpoint, therefore, high speed in both relays and circuit breakers is very desirable.

Extensions of systems and interconnections have introduced operating problems important from the standpoint of stability. The greater complication of the systems requires the human element to a greater extent than hitherto, and operating rules are being expanded accordingly. The method employed to maintain system frequency and to increase prime mover input importantly affects stability. Pertinent in this connection is the present trend toward the automatic control of frequency.

To insure stable operation it is obviously desirable to maintain a high ratio of generating capacity to connected load and a high ratio of excitation to load on the individual units. In the determination of these ratios other considerations will be controlling, but stability cannot safely be ignored. The increase in size of the individual generating unit makes these problems more important than formerly. Excitation of machines is usually determined from prescribed ranges of bus voltages, but this, unless carefully watched, is likely to subject some machines to unduly low excitation for either a heavy load or a light load condition. Consideration has been given to the interlocking of governor and voltage regulators to insure that adequate excitation is available before the prime mover input is increased. Loss of excitation is relatively infrequent, but when it does occur, severe system oscillations are produced.

The theoretical investigation of stability has proceeded to a point where fundamental operating data are urgently needed. Information as to the operation of systems has been obtained in the past principally from indicating and graphic instruments which have

been provided for the convenience of the operators. During the past few years a number of instruments with speed-up devices has been used, but the general results have not been entirely satisfactory because of the delay in starting the device and the inaccuracies in the measuring elements. Recently these objections have been reduced by the use of an oscillographic type of instrument, and the tendency is to use such devices where transient records of disturbances are desired. The importance of records of this nature is becoming more apparent in reconstructing the nature and extent of system disturbances, particularly where considerable power is being transmitted over some distance. With such data available it will be possible to place the design requirements upon a sounder basis; for example, it should be possible to determine whether the basis for maintaining stability should be predicted upon a single fault to ground as is commonly done at present, or upon the less frequent double fault to ground. Such data will also make it possible in many cases to estimate from oscillation with existing loads, the probable system disturbance with future loads.

GENERAL CONCLUSION

The expansion of the interconnection of systems has brought numerous problems to the engineer for solution and it is to be noted in the foregoing subcommittee reports and the several papers presented before the Institute that fundamentally different ideas of system developments have been brought out to meet the ever increasing demand for higher continuity of service and greater flexibility of supplying relatively large blocks of load from a network system. Your committee expects rapid strides to be made within the next few years in handling distribution problems and predicts radical departures from old methods and practises.

Discussion

F. W. Gay: Wherever it is possible to transmit power between two stations over two separate transmission lines on different rights-of-way, a method is available for protecting such twin lines against the disastrous flow of current over a flashed insulator string.

If each conductor from the source of power at the sending station and each conductor to the load at the receiving station is each separately connected to the mid point of one of six closely interlaced auto-transformers and a pair of conductors (one in each twin line) connect the start and finish of a transformer in a given phase at one station with the start and finish of a transformer in the same phase at the other station, and the entire six transformers are so connected, the desired result will be obtained. It will now be evident that on a system, grounded solidly or through the neutral resistance, a flash to ground on one line will ground an end terminal of each of the two auto-transformers connected to that line. The auto-transformer so grounded at the sending station will instantly act to step the power it receives from the station bus to twice normal voltage. This power will be transmitted at twice normal voltage over the connected conductor in the good (twin) line and will be stepped down to normal voltage by the auto-transformer at the receiving station. The only current that can flow to the fault is the charging current of the double-voltaged line and the magnetizing cur-

rent of the two auto-transformers. These currents can be picked up by separately insulated low-capacity low-voltage windings on the transformers at one end of the line, by suitably connecting these low-voltage windings to a voltage source of the same phase. It is obvious that with such a system, three lines may be simultaneously arced over provided no two such lines are connected to a single transformer. Power current cannot follow the arc. The arc should immediately extinguish. The opening of circuit breakers should not be required.

W. A. Del Mar: The summary of developments in cables is very complete as far as the work of the preceding year is concerned.

There is one thing, however, which I wish had been touched upon, because it is a very live subject to those who are interested in cable dielectrics. That is the question of what happens to a cable sheath when the cable is heated and cooled. There has been an interesting discussion between several English cable engineers, published in the *Electrical Review* of London, January 18 and 25, February 1 and 15, March 1 and April 26 of this year, and considerable amount of work along similar lines has been done in this country by various manufacturers, operating companies, and electrical testing laboratories.

One of these engineers, C. J. Beaver, referring to British practise, denies the commonly accepted belief that when a cable is heated the lead is stretched beyond the elastic limit. This engineer claims that lead has a real elastic limit and that it is quite considerable, *i. e.*, about 260 lb. per sq. in. He does not deny, however, that in American practise where higher temperatures are obtained, this elastic limit may be exceeded. He is taken to task by T. N. Riley, T. R. Scott, and H. G. Wood, and a very illuminating discussion results in which a considerable amount of experimental data is given which I believe is quite valuable.

One problem we have before us, is whether cable should be completely filled with oil compound or whether it should have a certain amount of air. We find considerable difference of opinion among engineers in this regard. The tests that have been made rather indicate that a certain amount of air is desirable in the insulation in order to make the cable satisfactorily pass an accelerated life test, but on the other hand, it has not yet been fully proved that these accelerated life tests are representative of the cable quality.

D. W. Roper: The Chairman of the Transmission and Distribution Committee, in his remarks, predicted that within five years most of the large cities of the country would be depending on overhead transmission lines for a part of their electrical supply. Some years ago the same indication appeared in the Chicago region shortly after 132 kv. had been adopted by a number of companies in this region as their overhead transmission voltage. It also appeared that it would be very desirable and economical to have such transmission lines brought directly into one of the generating stations, and this involved the use of 132-kv. underground cable. Some of the cable manufacturers thought that such cable would be too expensive to consider seriously, but their attention was called to the fact that the use of such cable would eliminate a substation at the edge of the city whose only function would be to step down the voltage from 132 kv. to a suitable voltage for underground cable extending to one of the generating stations. Under such conditions, the cost of the cable may not be a determining factor, as other conditions will offset, in whole or in part, the apparent high cost of the underground cable itself.

Within the next year 100,000 kw. at 132 kv. will probably be brought into Chicago on overhead transmission lines, and in each case there will be a few miles of underground cable continuing the transmission at full voltage to the nearest generating station. Within the next five years this figure may be multiplied by three or four. In one case which is in prospect, the distance is so great that 132 kv. is not an efficient transmission voltage, and it appears necessary to go to 220 kv. or some higher voltage. When that condition arises, we will be confronted with the same

conditions that arose in connection with the first 132-kv. transmission line, that is, the desirability of having the transmission line continued into the nearest generating station by means of underground cable and at full voltage.

The remarkable success of the 132-kv. oil-filled cable in Chicago and in New York, where some 54 mi. of cables have been operating for about two years without any electrical failures, indicates that the cable is being operated well below its safe limit. This indication has been verified by measurements which have been

made during the past two years on an experimental installation of similar cable at a location where there are laboratory facilities for measuring the dielectric loss of the ionization factor. As a result of these indications, we are now investigating the possibility of making cable for 220-kv. operating pressure so that when the occasion arises, the line may be brought into the nearest generating station by means of underground cable, and in this way avoid the transformer substation which would otherwise be necessary at the edge of the city.

Protective Devices

ANNUAL REPORT OF COMMITTEE ON PROTECTIVE DEVICES*

To the Board of Directors:

The work of the Committee this year has been: first, the revision of present and preparation of new standards; second, a survey and review of research and development made during the past year in the several fields covered by the Committee; and third, arranging for the preparation of papers for presentation before meetings of the Institute.

The work of the Committee, as organized at the meeting in New York in November 1928, has been carried out by subcommittees, each under the direction of its own chairman. The fields covered and the chairmen in charge of the subcommittees are as follows:

Lightning Arresters	Herman Halperin	Commonwealth Edison Company, Chicago, Ill.
Industrial Equipment and Service Protection	R. O. Muir	General Electric Company, Schenectady, N.Y.
Current Limiting Reactors	N. L. Pollard	Public Service Production Company, Newark, N.J.
Oil Circuit Breakers, Switches, and Fuses	A. M. Rossman	Sargent & Lundy, Chicago, Ill.
Relays	H. P. Sleeper	Public Service Electric and Gas Company, Newark, N.J.

The Subcommittee on Communication Line Protection which reported last year has been discontinued as it was felt its work overlapped with that of the Technical Committee on Communication Lines.

SUBCOMMITTEE ON LIGHTNING ARRESTERS

Work has been continued on the A. I. E. E. Standards for Lightning Arresters. Two preliminary reports of these standards have already been published, (one in 1926 and the other in 1928), under the title *Report on Standards for Lightning Arresters and Other Apparatus for Protection against Abnormal Transient Voltages*. Because of the wide variation in requirements and practises of arresters for all types of circuits, in the present revision the standards may be limited in scope to arresters for power circuits and the title shortened to *Standards for Lightning Arresters*. As soon as it is practicable, the subcommittee hopes to turn its attention to standards for arresters for other applications and to standards for other protective devices, such as surge absorbers, choke coils, ground wires, fused grading shields, etc.

*COMMITTEE ON PROTECTIVE DEVICES:

E. A. Hester, Chairman,		
Raymond Bailey, Vice-Chairman		
V. J. Brain, Secretary		
A. O. Cummins,	F. O. Harker,	R. O. Muir,
E. W. Dillard,	F. L. Hunt,	N. L. Pollard,
H. W. Drake,	B. G. Jamieson,	A. M. Rossman,
W. S. Edsall,	J. Allen Johnson,	A. H. Schirmer,
L. E. Frost,	S. M. Jones,	H. P. Sleeper,
E. E. George,	R. L. Kingsland,	R. M. Spurck,
James S. Hagan,	M. G. Lloyd,	E. R. Stauffacher,
H. Halperin,	J. B. MacNeill,	H. R. Summerhayes.

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

Research on lightning has been continued in the field and laboratory by the manufacturers, in several instances, in cooperation with a number of the operating companies. Extensive tests have been made on the transmission, reflection, attenuation, and effect on terminal apparatus of surges applied on full-sized transmission lines. These tests are being continued and are being correlated with the effects of natural lightning on the same or similar lines.

Further studies of natural lightning on transmission lines by the cathode ray oscillograph will be continued during the present lightning season, so that several records of great value and interest may be expected this year as a result of the extensive program. Investigations of surges, their effect on apparatus and diminution by arresters has been greatly aided by continued development in portability, ease of manipulation, and automatic timing features of cathode ray oscillographs. A new type which appears to have many good features has been developed by R. E. George of Purdue University.

A large scale and detailed program of investigation is still being actively pursued by one of the large operating companies on the causes of transformer failures on 4-kv. distribution circuits and their 115/230-volt secondaries during lightning storms and on the possible methods of reducing the number of service interruptions due to such failures. Studies are being made of the effects of resistance in the arrester ground, and laboratory and field tests are being made on the effect and practicability of lightning arrester protection on the secondary side of the transformers.

In the field of high-voltage transmission, work has been continued on the use of fuses in connection with grading shields on insulator strings. Recent developments indicate the feasibility of using expulsion type fuses as arcing horns at the tower end of the string. These developments indicate a tendency to build lightning arrester characteristics into the insulator string itself and perhaps in the future other elements will be developed for connection in series with or in shunt with part of the insulator string to accomplish this end.

There are several problems the solution of which will require further tests and study. Some of these are as follows:

1. *Gap-Setting.* The proper setting of gaps in series with arresters depends largely upon the type of arrester and its application. The application must take into consideration the maximum dynamic voltage, which is dependent on such factors as grounded or ungrounded neutral, relaying, arcing grounds, and also whether the plant is steam or hydro.

2. *Ground Resistance.* With the increasing size of power systems, the problem of obtaining good grounds

has become increasingly important. In the case of large stations, the expense of providing adequate grounding facilities is low enough relative to the total station costs involved so as not to be serious from an investment standpoint, but in the case of small stations, tower footings, etc., the cost of securing adequate ground connections may be high enough relative to the total investment to be rather serious.

3. Quantitative ratings with respect to impulse voltage of lightning arresters and apparatus to be protected in order to give greater assurance of protection.

All things considered the subcommittee feels that splendid progress has been made in the study of lightning and in apparatus and methods of mitigating its interference with power transmission. It looks forward with confidence to accelerated progress in protection against lightning in the immediate future.

Several valuable papers have been presented before the Institute on these and allied subjects, among which the following may be mentioned:

A Graphical Theory of Traveling Electric Waves, by V. Karapetoff, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 508.

Progress in Lightning Research in the Field and Laboratory, by F. W. Peek, Jr., A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 436.

1927 Lightning Experience on 132-Kv. Transmission Lines, by Philip Sporn, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 480.

Theoretical and Field Investigations of Lightning, by C. L. Fortescue, A. L. Atherton, and J. H. Cox, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 449.

Protection of Transmission Lines from Interruption by Lightning, by 1928 Subcommittee of Power Transmission and Distribution Committee, A. I. E. E. Quarterly TRANS., Vol. 48, April 1929, p. 487.

Rationalization of Transmission System Insulation Strength, by Philip Sporn, A. I. E. E. Quarterly TRANS., Vol. 47, Oct. 1928, p. 998, (Discussion p. 1009).

Relation between Transmission Line Insulation and Transformer Insulation, by W. W. Lewis, A. I. E. E. Quarterly TRANS., Vol. 47, Oct. 1928, p. 992, (Discussion 1009).

Symposium on Surge Voltage Investigation on Transmission Lines, A. I. E. E. Quarterly TRANS., Vol. 47, Oct. 1928, pp. 1111-1154.

A New Type of Hot Cathode Oscillograph, by R. E. George. Presented at the A. I. E. E. Regional Meeting, Cincinnati, Mar. 20-22, 1929.

Fused Arcing Horns and Grading Rings, by P. B. Stewart, A. I. E. E. J., May 1929, p. 390.

Investigation of Transmission Lines with Artificial Lightning, by K. B. McEachron and V. E. Goodwin, A. I. E. E. J., May 1929, p. 382.

Lightning Studies of Transformers by the Cathode Ray Oscillograph, by F. F. Brand and K. K. Palueff, A. I. E. E. Regional Meeting, Dallas, Texas, May 7-9, 1929.

SUBCOMMITTEE ON INDUSTRIAL EQUIPMENT AND SERVICE EQUIPMENT

Addition to A. I. E. E. Standards No. 15 (A. E. S. C. C-19) Industrial Control Apparatus has been completed, and will be submitted to the A. I. E. E. Standards Committee for joint action with N. E. M. A.

These additions are considered necessary to the Industrial Control Standards inasmuch as there is no standardized basis of short-time current rating or short-circuit interrupting rating of contactors and consequently information is not available whereby contactors might be properly applied.

A paper dealing with the general development and application of industrial control equipment and protective devices is being prepared under the auspices of this committee. Little has been published on this general subject, particularly with reference to the application of contactors, and it is felt that this paper will be of material assistance to engineers and will stimulate progress along the right lines in industrial equipment and service protection.

SUBCOMMITTEE ON CURRENT-LIMITING REACTORS

Some thought has been given to new standards for current-limiting reactors, but it has not been considered practicable to draw any up at the present time.

Last year's report called attention to the progress being made in the field of oil-insulated reactors. This progress has continued, large oil-immersed reactors having been built during the last year for circuit voltages ranging from 2.3 kv. to 73 kv., and in one instance for as high a circuit voltage as 120 kv. This type of reactor has increased the field of application of current limiting reactors, since it can be designed for higher voltages than the dry type and is particularly adaptable for outdoor service.

In the case of the 120-kv. circuit mentioned above, the reactors are used for sectionalizing the 120-kv., 60-cycle bus of a generating station having a capacity of 375,000 kv-a. Each reactor is rated at 2800 kv-a. and introduces 10 per cent reactance at 75,000 kv-a.

During the past year there has been a considerable increase in the number of dry type reactors installed with a marked increase in the use of reactors for grounding the neutral at generating stations.

Two, and possibly three, papers will be published and presented before the Institute in the near future under the auspices of this committee.

SUBCOMMITTEE ON OIL CIRCUIT BREAKERS, SWITCHES, AND FUSES

The preparation of more comprehensive standards for fuses is now under way. It is expected that the preparation of these standards will be greatly facilitated by tests which have been conducted during the past year by several operating companies on fuses rated at voltages from 2.3 to 66 kv. A series of tests has also been conducted on fuses of potential transformers.

Several manufacturers have increased their gen-

erating facilities available for testing oil circuit breakers and have carried out, on a large scale, systematic programs of testing their standard circuit breakers. These tests have resulted in improvements in details and have given an increased knowledge of the safe interrupting capacities of these oil circuit breakers.

Field tests have been extended to include 220-kv. oil circuit breakers, and additional tests are scheduled to be made this year. It is expected that the results of these tests will be published as soon as the tests are completed and the data available for publication.

Increased interest has also been taken in higher speed oil circuit breakers for use on high-voltage transmission lines to improve stability of operation by the more rapid clearing of faults.

Circuit breakers of extremely high speeds have been developed for electric railway protection. Tripping speeds as high as 0.012 to 0.016 sec. for a d-c. breaker and 0.04 sec. for an a-c. breaker have been obtained.

The past year has shown an increased interest in metal-enclosed switching structures. A number of the manufacturers of switching equipment in this country are now building structures of this type. A 33-kv. structure has been in successful operation for over a year and several others are now being built for this voltage. A 22-kv. structure of the oil filled type, the largest structure of this type to be installed in this country, will handle the entire output of one of the largest power stations in the Middle West. The first section comprising 23 units was placed in service this Spring. Several hundred units of this type have also been installed on 2300-volt circuits.

These structures greatly reduce the hazard to human life because the live parts are inaccessible and because the moving or removable parts may be interlocked to prevent incorrect operations. Most of the structures have been built without disconnecting switches, the oil circuit breaker being disconnected from its connections with the bus bars and circuits by being moved bodily away from its operating positions. This has permitted a very simple system of interlocking with the use of but five or six sturdy parts.

The metal-enclosed design is completely fabricated in the shops of the manufacturer, and the equipment is shipped in a semi-assembled condition. These factors tend to promote standardization of design and eliminate a large amount of field work, both of which should in time be reflected in lower costs of switching structures.

Papers on theory, design, and test of the Deion circuit breaker were presented at the Winter Convention of the Institute. This development appears to be a notable contribution to the circuit breaker art, as it eliminates the use of oil, and while at present confined to relatively low voltages, it is hoped that it will later be found possible to adopt it for use on higher voltages. It is also hoped that this development will stimulate further research which may lead to the discovery and

application of other new principles for interrupting power circuits.

Through the efforts of the members of this subcommittee, the following papers have been submitted for presentation before the Institute some time during the coming fall or winter:

A Method of Fuse Testing, by B. M. Jones and E. H. Coxe.

Fuse Tests, by S. Murray Jones, supplemented by comments on recent oil circuit breaker tests.

Potential Transformer Fuses, by H. P. Sleeper and M. F. Riley.

The Effectiveness of Different Types of Barrier Construction in Switch Houses, by P. H. Adams and B. M. Jones.

SUBCOMMITTEE ON RELAYS

The feasibility of standardizing the operating characteristic of relays of different manufacturers has been investigated. This refers to the standardization of characteristic relay curves, operating current values of relay indicators, and various other characteristics of relays which are possible of standardization. It is apparent that the subject is one which will require considerable discussion by the members of the Institute before a representative consensus of opinion can be obtained, and as sufficient data are not yet at hand, it will be desirable to continue the work of this group for another year.

A review of protective relay schemes in use at this date indicates that there have been no radical changes in relay practice made in the past few years. However, there have been some new schemes introduced and the trend at the moment is a departure from the old standard schemes and is worthy of note.

The great majority of all relay installations in service at this time on transmission lines is some form of the so-called time differential system whereby selectivity between adjacent breakers is secured by the use of selective time settings. This involves the use of overcurrent and directional overcurrent relays in the same manner as has been used for many years heretofore. This system, of course, has the disadvantage of limiting the number of sectionalizing points in series by reason of the cumulative time settings at the source end. It has the further disadvantage of requiring time settings in excess of instantaneous settings.

To enable instantaneous settings to be used with the resulting increase in stability to power systems and minimizing of damage at the point of fault, there has been a tendency to use increased number of installations of differential schemes of transmission line protection. The series scheme of differential protection of transmission lines,—namely, pilot wire relaying,—has never found much favor in this country, although one operating company reports that it has used this method extensively on its 12-kv. loops out of substations, and the scheme has been quite satisfactory. They have

adopted recently the use of pilot wire protection on 66-kv. lines and installed several hundred thousand feet of such pilot wire last year. Modifications of the pilot wire scheme are becoming more in favor, however, as indicated below. The scheme of parallel differential protection of transmission lines, where one line is balanced against another, is the form most commonly used in this country and its use has increased considerably in the past few years.

At this time there is a very definite trend toward the use of schemes of transmission line protection which have not been named but might be called "independent" schemes. By this is meant schemes of relay protection wherein the protection of one section of line is entirely independent of that on an adjacent section. The pilot wire scheme falls within this category but as indicated above has never been commonly used. The impedance relay is a scheme embodying some of the features of this type of protection, and its application is slowly increasing. It is perhaps the simplest scheme of protection that is available at the moment. One of the most interesting applications of this type of protection is a case where the short-circuit current under certain conditions may be less than the full-load current. Here impedance relays are intended to be used for short-circuit protection, which are normally short-circuited out of service by fault detector relays. The latter are operated either by low voltage or the presence of short-circuit current which cuts in the impedance relays and allows them to operate during fault conditions.

A further and more elaborate scheme of this type is one which is now being used on a small scale and has possibilities for improvement and application in the future. This is a modification of the pilot wire scheme where the pilot wires are replaced by high-frequency oscillations on the transmission wires themselves. Two schemes are in use, one a high or radio frequency scheme, and the other a low or audio frequency scheme, both of which are fundamentally the same in operation. At the present time, auxiliary equipment of considerable cost and size is required at the line terminals to enable this scheme to function properly, and tends to limit its use. However, it is probable that these schemes will be perfected and fundamentally they seem to offer the most promising solution for future protection problems, particularly of the more complicated type. They embody all of the most desirable characteristics of relay protection; namely, high speed of operation, independent settings, and no limitations as to numbers of stations in series. It is probable that the future trend of the art will be definitely in the direction of applications of this so-called independent scheme of relaying.

There is a growing tendency toward recognition of the importance of bus protection in high-tension stations. Heretofore, the protection of busses in such stations was considered unnecessary, but the increasing capacities involved, with the resulting seriousness of outages,

has urged the use of this type of protection. It usually partakes of the form of series differential protection. For this protection, and also for the protection of transformer banks and rotating machines, the use of ratio differential relays is becoming more common and superseding the old type of differentially connected over-current relays.

A scheme for securing overcurrent protection on balanced lines without the use of additional relays has been developed. The high- and low-set directional relays are connected in much the usual manner, except that the balance point is made at the mid-point of an auto current transformer, and the overcurrent element of a high-set relay is connected across the entire winding of the auto, instead of in the balanced circuit. It is obvious that the high-set relay receives line current at all times and is connected to trip both breakers. This of course requires the use of a double-contact directional element on the low-set directional relay.

A new scheme of protecting load ratio control units has been developed, using a restrained overcurrent relay. One winding is connected to the exciting winding of the load ratio control unit. The other winding is connected to the line. The effect is to change the setting of the relay so that a percentage tripping characteristic is obtained.

A scheme for detecting ground faults in apparatus by using a restrained current relay with multiple restraining coils has been developed. These coils are connected to the phase current transformers and the operating coil is energized by the residual current.

Radio differential relays have been applied to bus differential protection and their characteristic used to tend to eliminate incorrect operations due to secondary wiring troubles.

There are also two new types of network relays. One of these is designed to operate on high reverse current at normal voltage and is still very sensitive at short-circuit voltage. The other is for the protection of low-voltage a-c. networks, the feeder transformers of which are connected in delta on the low-voltage side and with the middle tap of one winding brought out to obtain lighting voltage. It is essentially a combination of three relays: a power directional, an overcurrent, and an overvoltage, set to trip quickly on transformer or feeder faults, but not being sensitive to small reversals of power.

Several existing types of relays have been modified and improved to give better operation. The ratio differential relay has been modified for application to the protection of three-winding transformers. The induction type overcurrent relay has been speeded up so that it will operate in approximately three cycles. The residual directional relay has been modified so that it will operate correctly over an extended power-factor range. Various types of condenser devices have been developed for securing potential for relay operation without the use of high-tension potential transformers.

The most common of these is in connection with the condenser type high-voltage bushing, but other condenser types of devices have been developed for this same purpose.

A paper entitled *New Directional Relay Schemes*, by

E. E. George and R. H. Bennett, is in preparation and will be presented sometime in the near future. Two other papers are also in preparation for presentation before the Institute, dealing with relay acceptance specifications and with relay experience.

Research

ANNUAL REPORT OF COMMITTEE ON RESEARCH*

To the Board of Directors:

It is now generally recognized that progress in science and industry depends largely on research. Electrical engineering in particular must trace practically all its advances to some form of research, whether it be pure or applied. Accordingly a complete report on research in this art must necessarily involve practically all the developments in its various branches such as communication, machinery, transmission, etc. Inasmuch as this is particularly material for the Institute committees involving these branches, an attempt is made in this report merely to mention the various research bodies and their work in general, and to list briefly the outstanding achievements in engineering and physical research during the past year.

Considerable assistance was received from various members of the Research Committee in the preparation of this report, particularly Messrs. V. Bush, S. M. Kintner, M. G. Lloyd, D. W. Roper, C. E. Skinner, R. W. Sorensen, and J. B. Whitehead. Several non-members provided valuable contributions, particularly Doctor W. F. G. Swann of the Bartol Foundation.

RESEARCH ORGANIZATIONS

The National Research Council has been very active in sponsoring research and its committee on Electrical Insulation has started an extensive program. At a two-day symposium conducted in Baltimore last fall by this committee, papers were presented reporting the results of studies of the mechanism of cable deterioration, the products of the breakdown of liquid dielectrics, the current wave form in dielectrics under high stress, the influence of air and moisture in impregnated paper insulation, short time absorption curves in composite insulation, the relation of dielectric absorption and dielectric loss, anomalous conduction in liquid insulation, gaseous ionization in cables, and the breakdown of solid dielectrics. At a second symposium, conducted during the Washington meeting of the American Physical Society, papers were presented on the mechanical and electrical strength of dielectric crystals, electrical convection in oil, effect of temperature, pressure, and frequency on rubber, influence of surface and space charges on the apparent conductivity of dielectrics, electron bombardment of hydrocarbons, and the de-

pendence of dielectric polarization upon molecular condition.

The Bartol Research Foundation of the Franklin Institute under Doctor Swann carried out a valuable research program during the past year. Among the important subjects investigated were the following: phenomena in the electric arc, reflection of atoms on crystals, excitation of atoms by electron impact, possible influence of cosmic rays on radioactivity, production of X-rays by protons, influence of a-c. fields on light transmission through water, corpuscular radiations of cosmic origin, energy lost by electrons passing through thin foils, polarization of light produced by impact of cadmium atoms with excited mercury atoms, photoelectric effect in thin films of potassium and sodium, and absorption of cosmic radiation in air. A number of theoretical problems was considered mathematically such as the scattering of electrons by atoms, theory of Compton effect produced by standing electromagnetic waves, possibility of detecting individual cosmic rays, relation between mass and energy, and ionization by an electron traveling with speed comparable with that of light.

Several noteworthy research accomplishments were made at the Bureau of Standards during the past year. The corona voltmeter was investigated, and a careful study made of the effects of pressure, temperature, and humidity on its accuracy. A redetermination of the absolute value of the international ohm was carried out. Important work was done toward developing a suitable radio beacon for aircraft. An electrical seismometer also was devised which is proving to be a very satisfactory instrument for recording earth movements.

ELECTRICAL ENGINEERING RESEARCH IN THE COLLEGES

During the past year an a-c. calculating board was developed at the Massachusetts Institute of Technology for representing in miniature almost any power system. The device offers a practical means of solving easily the steady-state problems of current and power division, system voltage, load balance, power factor adjustment, and the transient problems of both symmetrical and unsymmetrical short circuits with attendant considerations of system stability.

Important investigations in the colleges are being made of solid and liquid insulations, particularly as they relate to underground cables. Under the auspices of the National Electric Light Association, the Association of Edison Illuminating Companies, and the American Institute of Electrical Engineers, a study of thermal characteristics and methods of measurement is being made at Massachusetts Institute of Technology, the effect of residual air and moisture at the Johns Hop-

*COMMITTEE ON RESEARCH:

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V. Bush,	S. M. Kintner,	R. W. Sorensen,
E. H. Colpitts,	M. G. Lloyd,	T. S. Taylor,
W. F. Davidson,	Chester W. Rice,	J. B. Whitehead.
W. P. Dobson,		

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

kins University, and ionization characteristics at Harvard University.

Under the Utilities Research Commission (consisting of representatives of the Samuel Insull utilities) studies of methods of detecting cable failures and of physical properties of lead sheaths are being made at the University of Illinois, at Johns Hopkins University of the properties of impregnated paper, and at the University of Chicago of the fundamental significance of dielectric strength.

A large part of the research sponsored by the National Research Council and the Engineering Foundation is being conducted in the college laboratories, particularly in the East and Middle West.

Several of the college engineering laboratories on the Pacific Coast have been active in research problems during the past year. Some of the accomplishments of note were the study and analysis of Lichtenberg figures at the University of Washington; the X-ray studies at the California Institute of Technology, using the million-volt transformer set for tube excitation; and the investigation and measurement of high-voltage flashovers at Stanford University, where 60-cycle flashovers of gaps up to 36 ft. were made, the longest yet accomplished at commercial frequencies.

OUTSTANDING RESEARCH ACCOMPLISHMENTS IN ELECTRICAL ENGINEERING

Considerable progress was made during the past year in the study of lightning on transmission lines. Much of this was made possible through the adaptation of the cathode ray oscillograph for direct recording on power lines. Lightning waves recorded in lines have been duplicated in the laboratory and their effects on transmission lines, insulators, insulation, transformers, and protective apparatus studied at will. For making these laboratory tests a lightning generator producing 5,000,000 volts was constructed. Smaller portable lightning generators were also produced and used for putting surges at desired points on lines.

By means of surge voltage recorders and klydonographs, distributed at intervals on several power systems, valuable data also were obtained on the crest values, polarity, attenuation, and frequency of lightning surges on lines.

As a result of lightning research, it is now possible to design transmission lines, and to coordinate the line and apparatus insulation so as to have power systems which are highly resistant to lightning.

A well coordinated program in lightning research is being continued. A considerable part of the field work is being done on transmission lines in cooperation with operating engineers.

A number of advances was made in transformer design last year. Among these was the development of the non-resonating transformer. The object of this type is to cause a uniform voltage distribution through-

out the windings under all frequencies and lightning surges.

Several improvements were made in switches and circuit breakers during the past year. One achievement in this line was the development of the Deion circuit-breaker switch. In its primary application to practise it has been designed for use up to 15,000 volts; its operation making use of a series of extremely short gaps in air.

In the field of electrical machinery numerous advances were made. Noteworthy among these was the successful development and operation of a 10,000-kw. mercury turbine, whose efficiency exceeded the previously predicted values. The popularity of the high pressure turbine also increased, as may be witnessed by the fact that five new 1200-lb. units were designed during 1928. The development of hydrogen-cooling for reducing losses and increasing the capacities of generators and synchronous condensers made appreciable strides. Units up to 20,000 kv-a. using this method of cooling were built during the past year. The tendency to use higher generated voltages with large capacity units for certain classes of service continued. Several 22,000-volt generators were designed and installed in this country, and one 33,000-volt unit was placed in operation in England, connection being made directly to an underground cable system with no intervening transformer.

Aviation profited appreciably from research developments carried out last year in the Bureau of Standards and in the laboratories of the several larger industrial concerns. The principal advances consisted of additional navigational aids for commercial aviation. Here radio contributed principally in improving communication, course navigation, and fog landing. Better facilities for navigation and landing in the fog were added by the development of neon light beacons and markers. A method of depth-sounding in the air to enable aviators to determine their altitude was devised. The procedure consists in sending out radio waves from the airplane, which are reflected from the ground and received again by the plane. A magneto compass also was designed, weighing less than one-fifth of the present earth-inductor compass. A means of accurately measuring the amount of gasoline was devised making use of electrical impulses transmitted from diaphragms located in the airplane tanks.

Much work was carried out during the year in perfecting and applying photoelectric devices to many uses, such as smoke detection and measurement, control of illumination, operation of traffic devices, etc.

Marked progress was made on the question of television and far greater use will undoubtedly be made of it in the near future. Appreciable advances were made in the speed and convenience of picture transmission, by both wire and wireless, during the year.

The great increase in popularity of the talking moving

pictures furnished added stimulus to research in that line so that considerable improvement is expected in this art.

Decided progress was made in metallurgical work through the wider application of inductive heating, both in furnaces of the vacuum type and the non-vacuum type.

The increasing temperatures, pressures, and speeds of electrical machinery have made it necessary to give added study to the characteristics of metals under high temperatures and mechanical stresses. Results of great value have been reported.

Research in magnetic materials and magnetic phenomena was continued, and much was added to our understanding of these vital subjects.

Laboratory devices for the analysis of noise were developed and studies made of the sources of noise in machinery, and its elimination.

OUTSTANDING RESEARCH ACCOMPLISHMENTS IN PHYSICS

Light and Spectroscopy. Michelson, Pease, and Pearson, University of Chicago and Mount Wilson Observatory, have repeated the Michelson-Morley experiment and find no shift that can be interpreted as arising from an ether drift. This completely agrees with the original results obtained by Michelson and Morley and also seems to add strength to the relativity theory which was developed to explain the earlier experiments. (*Trans. Optical Soc.*)

The Indian physicist, Raman, has shown that light scattered from many substances contains not only the original frequencies of the incident light, but also the other frequencies differing from it by the natural frequencies of the scattering substance. This effect has been used by Raman and others to study the natural frequencies of many substances as well as to extend further the laws of scattering.

Our knowledge of the structure of many diatomic molecules has been materially extended by the analysis of their band spectra by Mulliken and others.

McLennan and his students have continued their studies of the Aurora and have definitely fixed the position of the unknown auroral lines in the structure of the oxygen atom. (*Proc. Royal Soc.*)

Study of the band spectrum of oxygen by Babcock and Dieke of the Mount Wilson Observatory and Giauque and Johnson of the University of California have shown the presence of an isotope of atomic weight 18. This heavier isotope is about one two-thousandth as plentiful as the isotope 16 so its presence had not been detected by mass spectrograph methods. (*Nature*, March 2, 1929.)

Bowen, California Institute of Technology, has shown the presence of sulphur in the nebulae, by the identification of some more unidentified lines of the spectrum. (*Nature*, March 23, 1929.)

J. W. DuMond of California Institute of Technology

has developed an experimental method based on the study of the spectral distribution of Compton modified radiation for determining the velocity distribution of both bound and conduction electrons in metals and of electrons in non-metals. (*Physical Rev.*, May, 1929.)

Absolute measurements of X-ray wavelengths have been made by means of an optical grating. By this means it is possible to get an independent determination of the charge on the electron.

Conductivity. Bridgman, of Harvard, continued the experiments on conductivity and thermoelectric effects in anisotropic single-crystals of metal and showed that the electronic effects in metals follow the crystal-symmetry. (*Nat. Academy of Science*, Vol. 14, p. 943, December, 1928.)

Kapitza has made further experiments on variations of resistance of metals in very strong magnetic fields up to 300,000 gauss. Bismuth lost its conductivity. These experiments may explain much about the conductivity of electricity in metals. (*Proc. Royal Soc.*, Vol. 123, p. 292.)

J. B. Johnson of the Bell Telephone Laboratories has been able to detect and measure the random motions of the electrons in a wire due to their temperature energy. From these measurements it is possible to determine the value of Boltzmann's gas constant. These results lend considerable support to the idea that the conduction electrons in a metal follow the laws of an electron gas. (*Physical Rev.*, Vol. 32, 1928.)

Electronic Emission. R. A. Millikan and C. C. Lauritsen, California Institute of Technology, constructed an apparatus in which electrons were pulled from the electrodes by strong electric fields. The electrons so extracted were of such high velocities as to be capable of producing X-rays with wavelengths comparable to cosmic radiation.

DuBridge gave the first reliable evidence that the photoelectric threshold has exactly the same values as the thermionic work-function for the same metal. (*Physical Rev.*, Vol. 32, p. 961.)

Cardwell showed qualitatively a change of the photoelectric and thermionic emission at the change of an allotropic modification of the cathode.

A. Goetz, California Institute of Technology, gave the experimental evidence that the photoelectric emission and the threshold changes at the melting point and transition point of tin are such that the larger the atomic distance in the cathode the smaller the work function of the metal. This shows that the mechanisms of the photoelectric and thermionic effects are of the same nature. (*Physical Rev.*, Vol. 33, March, 1928, p. 373.)

Lukirsky and Prilezaev succeeded for the first time in measuring the loss of energy of photoelectrons crossing the cathode towards the surface, thus showing that the photoelectric effect is not a pure surface effect, as has been generally considered.

Work in Theoretical Physics. The so-called "principle of uncertainty" stated by Heisenberg has gained general

recognition as a fundamental principle of physics. According to this principle, it is impossible to determine at the same time the position and velocity of a particle with absolute accuracy. The product of the uncertainty in position and the uncertainty in velocity can never be less than Planck's constant h . This is because the method of observation itself affects the quantities to be measured.

The fundamentals of quantum mechanics have remained essentially unchanged, but many applications have been made. Heisenberg has given a striking theory of ferromagnetism based on the magnetic electron as the effective magnetic unit. The electrical resistance of a metal has been explained as due to the diffraction of the electron waves by the crystal lattice. Many of the other electrical properties of metals seem to find a satisfactory explanation on this basis. Neumann and Wigner have shown that all of the known qualitative rules for the analysis of spectra can be derived directly from the Schroedinger equation, and it has been possible to derive some quantitative relationships between spectral terms for spectra more complex than hydrogen. Rubinowicz has shown how the intensities of forbidden transitions may be predicted, so that from the appearance of such lines in the nebulae the physical state of the material may be inferred. Sommerfeld has applied the quantum mechanics to explain the observed distribution of photo-electrons ejected from gases.

The theory of relativity has received an important

contribution from Einstein who has been able to give a unified treatment of the gravitational equation and the electromagnetic equations.

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Discussion

F. C. Caldwell: Referring to the inter-relation of research in different fields of science and engineering, it may be well to call attention to an organization that is just going into operation in Columbus, Ohio. This is the Battelle Memorial Institute, founded by Gordon Battelle as a memorial to his father. Mr. Battelle was associated with the metallurgical industry and bequeathed a substantial amount for the construction and operation of a research laboratory.

Part of the income from this fund will be spent under the exclusive direction of the Battelle Institute. Industrial research will be conducted on the fellowship plan.

While this laboratory is, as I say, primarily metallurgical, the fact that it is no longer possible to separate sharply the different fields of research, makes it inevitable that there will be cooperation with other research organizations along border lines. The electrical engineering profession should therefore know of this Institute, and should look upon it as one of the possible sources of information in those fields where metallurgical and electrical engineering meet.

Transportation

ANNUAL REPORT OF COMMITTEE ON TRANSPORTATION*

To the Board of Directors:

Following established precedent, your Committee submits a brief review of the year's development in the application of electricity to transportation.

STEAM RAILROAD ELECTRIFICATION

Pennsylvania Railroad. The Pennsylvania Railroad has completed the electrification of its suburban service from Philadelphia to Wilmington, Delaware, on its main line to Washington, and to West Chester, Pa., on the Wawa Branch. The 11,000-volt, 25-cycle, single-phase system with overhead catenary used is in accordance with the original electrification work on the Pennsylvania in the vicinity of Philadelphia.

Of far greater importance, however, is the announced program and actual starting of work on the electrification of the entire road train service, freight and passenger, between New York and Wilmington, Delaware.

The project covers the passenger and freight service on 325 mi. of line and 1300 mi. of track, beginning at Hell Gate Bridge, New York, where connection is made with New England, and extending west and south to Wilmington, west from Philadelphia on the Main Line in the direction of Harrisburg as far as Atglen, and the low grade freight lines which join at Columbia, Pennsylvania, and connect the cities of New York, Philadelphia, and Wilmington with the West.

Work is already under way on the 132,000-volt transmission line through Philadelphia for the extension to Trenton.

Great Northern Railway. The Great Northern Railway has completed and placed in service the extension of the present single-phase electrification through the new tunnel from Scenic to Berne and then east to Wenatchee. This required the abandonment of its old line from Scenic to Cascade through the snow sheds, which electrification was completed about two years ago.

All traffic is now handled between Wenatchee and Skykomish with motor-generator locomotives having d-c. traction motors, the overhead contact system supplying energy at 11,000 volts, 25 cycles, single-phase.

Boston, Revere Beach & Lynn Railroad. This narrow gage line has completed its electrification of 15 route miles, using 600-volt d-c. overhead catenary system with multiple-unit operation.

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Richard H. Wheeler,

Sidney Withington,

Presented at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

Cleveland Union Terminal Company. In connection with the building of a combined terminal station and office building in the heart of the business district of Cleveland, it is necessary to handle all trains electrically. Through passenger trains of the New York Central, C. C. C. & St. L., and N. Y. C. & St. L. will be so handled through the city. It has been decided to use 3000 volts direct current with overhead catenary system. Twenty-five 204-ton passenger locomotives, with a rating of about 3000 hp. each, have been ordered, and active work on substations and distribution system started. Power will be purchased from the local power company.

Interurban and suburban trains will also use the station over separate tracks with 600-volt d-c. overhead trolley construction.

Reading Company. The Reading Company has started construction on the Philadelphia Suburban Electrification, which, initially, will include multiple-unit service from the terminal in Philadelphia to Chestnut Hill, Lansdale on the Bethlehem Branch, Hatboro on the New Hope Branch, and Langhorne on the New York Branch. This electrification was decided on not to meet any particular operating difficulty or municipal requirements, but to furnish a better service at a lower operating cost and with a hoped for increase in traffic and revenue.

The initial installation will consist of 50 route miles and 110 track miles, and the 11,000-volt, 25-cycle, single-phase system will be used.

Delaware, Lackawanna & Western Railroad. This company is actively engaged on the design and construction work covering the electrification of its suburban service with multiple-unit car trains from its Hoboken terminal to Dover, New Jersey, via Morristown; also the Montclair Branch and the Passaic & Delaware Branch. The running tracks between West End Junction and Kingsland are included in the program, as the inspection and repair facilities are to be located at the latter point. Certain freight movements between Secaucus and Hoboken Yards will be made electrically.

Power will be supplied through five substations at 3000 volts direct current to the catenary system. The program calls for the electrification of 150 track miles of main line and 25 miles of yards and sidings.

City of Rochester. The city of Rochester has completed and put in service an electrified railroad through the city, in the bed of the old Erie Canal, the right of way being purchased from the State. A modern boulevard has been built over the tracks for a considerable distance in the heart of the city.

The line is nine miles in length with two tracks the

full distance, one additional freight track for seven miles, and two other freight tracks for $1\frac{1}{2}$ miles. Inter-change tracks with steam railroads are provided. Frequent rapid transit cars are operated.

The overhead construction is of the catenary type using three wires with one contact wire. Inclined catenary is used on all curves except the slight ones at station approaches. Operation is at 600 volts direct current.

DIESEL-ELECTRIC LOCOMOTIVES

The development of oil-electric locomotives using prime movers of the Diesel type is continuing. A 300-hp. prime mover is most in use to date, one manufacturer having delivered 25 locomotives, weighing about 60 tons, each equipped with one 300-hp. Diesel engine with generator and d-c. traction motors.

Eight locomotives with the same type of power plant, but in duplicate, (the locomotive weighing about 108 tons), are also in service. This is in addition to the New York Central combination third rail, overhead, and storage battery locomotive equipped with the same type of 300 hp. Diesel engine with generator for operation off the trolley or third rail and for charging the battery.

The New York Central has recently accepted delivery of a Diesel-electric locomotive for passenger service on its Putnam division. The engine is a four-cycle air-injection Diesel of the 12-cylinder V type with a full-load rating of 900 b. hp. On the same division is also a freight locomotive with a six-cylinder 750-hp. solid-injection Diesel. Electrical equipment covers a main generator and an auxiliary generator direct-connected to the engine, four d-c. traction motors, control equipment air compressors, and auxiliaries.

Another manufacturer has supplied the Long Island R. R. with an articulated locomotive for switching purposes, equipped with two 330-hp. Diesel engines and electrical equipment. The complete locomotive weighs 87 tons.

The largest single-unit Diesel-electric locomotive built so far, however, is that purchased by the Canadian National Railways. It consists of two separate cabs, each cab containing a 12-cylinder Diesel engine of the solid-injection type rated at 1330 hp. at 800 rev. per min. Each unit weighs 325,000 lb., of which 240,000 lb. are on driving wheels. The present gear ratio was laid out for high-speed passenger service.

Other experimental oil-electric locomotives of varied horsepower are in process of development.

GENERAL PURPOSE LOCOMOTIVE

The Commonwealth Edison Company has ordered for trial what might be called a General Purpose Locomotive. It will weigh 85 tons with all weight on drivers and is intended primarily for switching work. It can operate directly from the overhead at 1500, 750, or lower voltage. A storage battery having a capacity of 544 ampere-hours at the six-hour rate is provided,

this battery to be charged through a motor-generator set when operating under the wire, or from two 155-hp. gasoline engines driving generators. The engines can be operated with distillate fuel. The four motors are rated at 250 hp. each, at 750 volts, one-hour rating. This locomotive will be put in switching service on the Illinois Central Railroad in the near future, for trial.

RAIL CARS. DIESEL-ELECTRIC

The Canadian National Railways has in service 14 Diesel-electric rail cars, four, six, and eight cylinders each, with a rating of from 200 to 400 hp. They are continuing the use of the Diesel type of motive power rail cars and now have on order nine cars to be equipped with six-cylinder engines, rated at 400 hp., each at 900 rev. per min.

GASOLINE-ELECTRIC

Over 120 gasoline-electric rail cars primarily for branch line service were put in service during the past year.

They vary in weight, and also in power from 200 to 800 hp. in one- two- and three-unit power plants with individual engines rated up to 400 hp. The majority have single power plants with engines of from 275 to 400 hp., the tendency in the last year being toward the larger units. One company is putting out power plants of 135 hp. each, one, two, or three being used, depending on weight of car and desired trailer load. The largest cars have two of the 400 hp. power plants and are in service on the Chicago, Rock Island and Pacific Railway.

MARINE PROPULSION

The electric-drive airplane carriers Saratoga and Lexington broke all existing speed records for capital naval ships in their sea trials.

The use of turbine-electric drives for large ships and Diesel-electric drive for smaller ships, ferries, and tugs continues to grow.

CAR RETARDERS

Refinements have been made in the design of both electro-pneumatic and straight electric car retarders for regulating the speed of cars being operated over humps to classification tracks.

Where formerly all switches were controlled from one central point by electro-pneumatic or electric switch machines and where each cut of cars was accompanied by a car rider to control the speed of the cut, now a large yard may be handled from separate towers near the switches, each tower controlling a group of switches and retarders with car riders eliminated. Several such yards are in successful operation.

RADIO COMMUNICATION

Several installations of radio communication between locomotive, caboose, and station have been in successful operation. Apparatus is now available for radio communication, as mentioned above, between trains, and between hump engines and the various control towers.

CENTRALIZED OR DISPATCHERS CONTROL

The railroads are making great strides in the movement of trains by signal indication only and have made use of the recent developments in centralized or dispatchers control for this purpose.

It is now possible and practicable to control electrically from a central point all desired switches and signals over a considerable route mileage. This arrangement facilitates meeting and passing points and thereby decreases running times between terminals with consequent savings.

Between Stanley and Berwick, Ohio, on the New York Central Railroad, the principal switches, some 30 in number, with all signals, are controlled from one point. This covers 37 mi. of single track and three of double track.

There are over 20 installations of varying lengths in service or on order and the use of this scheme is growing rapidly.

TRAIN CONTROL

The orders of the Interstate Commerce Commission, covering the installation of train control on some 44 Class 1 Railroads have been complied with and there are now over 15,000 track miles equipped and about 9000 locomotives equipped. In addition, there have been voluntary installations covering over 3000 road miles and over 750 engines.

The installations cover continuous control, intermittent control, and speed control.

While no new orders of the Interstate Commerce Commission are contemplated, yet the Division of Safety is following up the whole subject and suggesting

further installations where, in their opinion, conditions warrant.

SUPERVISORY CONTROL

The use of supervisory control in the handling of substation and switching station apparatus has continued. The last year has seen considerable development work done on the so-called synchronous selector and relay types, with initial installation of the first mentioned on the Cincinnati Street Railway System, and of the second at the Grimm Avenue Substation of the Chicago Surface Lines.

MERCURY ARC RECTIFIERS

The use of mercury arc rectifiers has continued rapidly, there now being in the United States in the vicinity of 40 installations for street railway, interurban, and steam road electrifications. These are arranged for manual, semi-automatic, and automatic control. The tendency has been to increase the capacity per bowl, there being one installation by the Commonwealth Edison Company in Chicago, having a capacity of 5000 amperes at 600 volts in one bowl. This is an automatic station for railway use.

HIGH-SPEED CIRCUIT BREAKERS

The high-speed a-c. circuit breakers of both the air and oil type, as mentioned in last year's report, have been completed and are now in successful operation on the Wilmington and West Chester extension of the Pennsylvania single-phase electrification. These circuit breakers interrupt short circuits in a half cycle or less and are comparable to the high-speed d-c. breakers which have been in use on steam railroad electrification for the last three years.

The Engineer, Practical Idealist

President's Address*

BY R. F. SCHUCHARDT

THE Institute, meeting here in convention on the "stern and rock bound coast" of New England, finds itself on historic ground. In this region are located many battle fields, of arms and of intellect, that have left their deep impress on our civilization. The battle fields of arms are marked by monuments that are now shrines of an appreciative people. The battles of the intellect, though often accompanied by bloodshed, are not so well remembered. Bunker Hill is fresher in our minds than are Salem and Roger Williams, yet Williams' heroic struggle for freedom of thought paved the way for that later struggle marked by the shaft on Bunker Hill.

The freedom we enjoy today, freedom of thought and of political action, we owe to those who fought and suffered and bled in generations past. We are worthy possessors of our heritages only if we in turn give thought to the morrow, and in our work today plan so that the morrow will offer a richer life for our children.

Are we of the engineering kinship, who are presumably well trained to determine facts and to reason from them, giving sufficient thought to the morrow? It is well on this occasion, in the atmosphere of these significant historical surroundings, to pause a few moments before taking up the technical part of our work, to consider briefly some problems of this interesting workaday world of ours, to try to glean from the study some of the trends in our civilization and our relation to them.

If it is true, as Professor East has written,¹ that man stands today at the parting of the ways, with the choice of controlling his own destiny or of being tossed about by the blind forces of his environment, then it will be well for the engineer to concern himself more with the environment. He should take a larger part in the leadership seeking solution for the human problems that vitally influence the trends. Surely the bewildering complexities of today require clear thinking, and who is better fitted for a thoughtful analysis of the factors on which development and progress depend?

With this as a background, I should like to suggest some thoughts that appear worthy of your careful consideration.

The history of mankind shows a successive rise and decay of great civilizations. Reflection on this leads to the frequent questions: Is our civilization headed for decay? Are we also, like former ages, unable to bear up under prosperity and power? I shall not venture an answer, but let us consider

some facts. Earlier civilizations existed on relatively small areas. Today the entire world is a neighborhood—made so largely by the work of the engineer. Not only is it a neighborhood world but also a much more densely populated world, and the great increase in population, we are told, started with the industrial revolution in the eighteenth century—also based on the engineer's work. The engineer, responsible for so much that *is*, cannot shirk his responsibility for correct guidance of what *shall be*.

Our civilization has come to be known as the Machine Age and as such it is both lauded and condemned. President Glenn Frank* in a splendidly balanced analysis of the machine age and its trends, offers this comment:

"... the masses have more to hope for from great engineers, great inventors and great captains of industry than from the social reformers who woo them with their panaceas. The greatest social progress of the next fifty years is likely to come as a by-product of technical progress."

Even in the Orient, where the materialism of the Occident is thought to sound the death knell of the spiritual, we find the famous Chinese philosopher, Dr. Hu Shih, in agreement, for he sees science and the new technology as the forces which restored to man a sense of self confidence and thus created the modern civilization of the West. He concludes that inventors, scientists, and producers of goods deserve the blessings of their fellows as spiritual leaders.

Others of the interesting group that contributed to the symposium, "Whither Mankind," inspired and edited by Charles A. Beard, seem to concur. As Dr. Beard summarized in part; "They are not oblivious to the evils of the modern order, but they do not concede that any other system, could it be freely chosen in place of machine civilization, would confer more dignity upon human nature, make life on the whole richer in satisfaction, widen the opportunity for exercising our noblest faculties, or give a sublimer meaning to the universe in which we labor."

With these encouragements let us try to see some of the things about us as they are. Let each of us compare this world of our experience with the dream world of our ideals. Let us see if as engineers we have not an exceptional opportunity to gain in our individual lives that true satisfaction which comes from an attempt to leave the world a better place than we found it. But first let us recognize that an engineer today is far more than Treadgold defined him nearly a century ago. In

1. "Mankind at the Cross Roads" by Edward M. East.

*Delivered at the Summer Convention of the A. I. E. E., Swampscott, Mass., June 24-28, 1929.

*"Where is this Machine Age Taking Us" by Glenn Frank, in *The Magazine of Business*, Oct. 1927.

addition to "directing the powers of nature for the service of man" he now adds to the common welfare also in fields more human. He finds himself occupied at times in social guidance so that the tools he has provided shall be properly used.

One of the most significant and important trends of this day is the continuing movement of population from the rural regions to the urban, which, with the great increase in the world's population, is thus rapidly accelerating the growth of cities. The engineer's machinery makes it possible to provide the necessary food with the expenditure of a lesser manpower than formerly and his transportation developments readily bring the food to the urban population. But with rapidly increasing population the problem becomes more and more difficult.

Professor East cites figures to prove that the maximum food supply that can be produced on the land area of this globe available for that purpose will support a population of fifty-two hundred millions, a figure which at the present rate of increase, he says, will be reached in about a century. Long before that time it will become necessary to bring into production land which is now largely arid and difficult of access, and even then, occasional crop failures will result in widespread starvation.

We can leave to the medical profession and to the biologists the task of checking population increase, but let us engineers face some of the attendant problems. We are not directly concerned with the exact decade when world saturation will be reached but we are vitally concerned with the provisions for living and for advancing civilization while man's neighbors are crowding closer and closer. The marvels of science have lulled the layman into a false sense of security. They have given him faith to believe that with the scientist and the engineer on the job the future will take care of itself. Perhaps it will, but only if the thinkers and the doers of this generation and those who follow put themselves earnestly to the task. Intelligent thinking usually leads to intelligent action. No engineer worthy of the name can take a laissez-faire attitude on problems that deeply affect human welfare and progress.

How does the engineer picture the future city? Is it to be a mechanical Colossus full of ingenious provisions for commerce and industry, for housing and for getting about, or will it be a place where man still has some contact with nature? The growth of our cities is both upward and outward. The upward limit is moving higher and higher, for both business houses and multiple dwellings, and all of the ground area that was formerly devoted to low buildings is being covered by the higher structures. The engineering problems of transportation, of light and air and health for the highly congested population are not impossible of solution but we must admit that they are being taken care of only in part. Multiple decked streets above and below ground, huge ventilators, air conditioning

devices, artificial light and other necessary contrivances are relatively easy to plan, though some of them are very expensive to provide; but is the sort of civilization that is likely to develop in a city of that character the kind that makes for a richer and nobler living? Are we building the City and forgetting the Man, as Grosvenor Atterbury² suggests, and are we not fast losing our sense of values?

You remember the Greek legend of Hercules and his encounter with Antaeus, the giant whom Hercules met when on his trip to get the golden apples. Antaeus was a son of Mother Earth and each time he touched the ground his strength grew tenfold. Hercules wrestling with the giant noticed this increased strength so he finally caught him up and held him in the air. Then, no longer having contact with Mother Earth, the giant's strength sank and life ebbed away with it. Is this not symbolic of man's experience when contact with nature is lost? Can a life develop properly when shuttling in crowded cars, through crowded streets or supercrowded subways, between an office which sees the sun for twenty or forty minutes a day and an apartment home in a high building closely touching elbows with neighboring high buildings? Is there a social problem involved in such city building and has the engineer no concern in it?

Our physical surroundings, things we can change if we will, offer a fertile field for the interest of engineers with their vision and with their desire for lifting life to higher levels. I suggest that we give more study to this and similar city problems and that we occasionally discuss them at Institute meetings, especially in our metropolitan sections.

Let us consider some of the problems that are, as it were, at our elbow. One is that of automobile engine exhaust in our cities, which has received all too little attention. This presents a serious health problem in the deep canyon-like streets. Investigators of carbon monoxide poisoning declare that this deadly poison is often found in city streets in sufficient quantities to impair health, and in some instances to be the proximate cause of death. And with the traffic jams on country highways, the holiday outing is now far from a health trip.

While on the subject of air pollution let us in passing note the factory and the apartment house chimneys that still frequently belch forth dense clouds, often robbing man of beauty and of health. The engineer has provided a partial cure, but even our giant power stations, which receive the most expert engineering attention, still leave something to be desired.

There is another handicap to which little thought is given,—the deleterious effect of noise on the nervous system. Scientific tests have shown a marked reduction in labor efficiency due to noise, and British physicians have even advocated an act of Parliament

2. "Our Monster City and Its Life" in *N. Y. Times Magazine*, Jan. 13, 1929.

prohibiting needless noise in the interests of the nation's health. Certain it is that our present day business and professional life draws heavily on our nerves, and all too many men collapse under the strain. Relief from noise as one contributor to the strain is thus a direct public benefit.

And how much are we interested in the backyard regions of our industrial cities? Many of these reflect little credit on our advanced civilization. Disorderly dumpheaps and scrap piles are still all too common. They enrich no lives spent among them; rather they are likely to develop that element in our citizenry with which the forces of law and order are in constant conflict. The appalling waste that this entails affects much more than our taxes. Good housing and neighborhood cleanliness go far toward making life for the lowly conform more nearly to the picture of today's accomplishments that we paint with such pride.

The engineer knows that most of our cities have grown more or less hodge podge during the crude developmental years of our country. He knows also that correct growth demands guidance, and this means a city plan. Fortunately many cities, taking the lesson from the important European centers, have seen the wisdom of proper planning and are correcting misfits of earlier decades and are providing better guidance for the future. But the problem is today one of even greater extent—one of regional planning, and engineering enters largely into this also. Here is a field which arouses the enthusiastic interest of every true engineer. He realizes that the suburban regions are rapidly filling with dwellings and to some extent with factories. He knows that if life is to be lifted to better things these newer developments must be coordinated properly so health, convenience, beauty, and the opportunity for wholesome family life may all be properly provided for. In this and similar activities the engineer will seek the greatest dividends in terms of human happiness.

The increasing population, Professor East says, requires that each year forty million acres more must be tilled and harvested than the year before to provide sufficient food, and this clearly makes countries more and more dependent on one another and at times will shift the direction of the dependence. The engineer has brought countries together by rapid transportation, by land, by sea, and by air, and has tied them still closer by achievements in communication, and now even by international power lines. What can he do to hold them together as friendly neighbors? The answer here goes to the very bottom of man's relation to man.

The material work of the engineer deals with nature's laws. He knows he must understand these laws and must use truth in his work or it will fail. Engineering analysis applied to human relations similarly seeks to find the underlying laws. A study of past civilizations indicates that they failed because of violation of that basic social law which bids us do unto others as we would have them do unto us. Is it too idealistic to

expect improvement in our day to come as a result of more engineering in government, that is, more of the engineering method applied to the solution of questions that tend to bring discord between peoples and between people? There is encouragement in the statement made by Bertrand Russell,³ "I look, therefore, to the western nations, and more particularly to America, to establish first that more humane, more stable and more truly scientific civilization toward which, as I hope, the world is tending."

Technical achievement has almost eliminated manual drudgery. The habit of technology to be guided by basic law holds out promise that "man's inhumanity to man" may likewise be banished. Is this also too optimistic? Has human nature remained unchanged through the ages, as is so often stated? May I refer the pessimists, if there be such here, to any story that portrays life during earlier periods, as for instance, "Power" by Leon Feuchtwanger. The reader of this gripping tale of the ruthless standards of the eighteenth century will congratulate himself that he is living in the twentieth.

Our machine civilization is still young, and we can attribute to growing pains many of the conditions that today prevent man's best development. However, a look toward the horizon will show many encouraging signs.

Our country, appreciating the keen need of the time for the engineering approach to the important problems of state, has elected an outstanding engineer to the presidency. In other countries the engineer must similarly stand at or near the helm if this civilization is to survive. This does not mean that he alone is to be the savior of mankind, but in this age of cooperation, the engineer, together with the doctor, the lawyer, the economist, the sociologist and other trained minds, must apply himself to a scientific solution of social problems in addition to furthering material development. He must join forces with all those

" . . . whose law is reason; who depend(s)
Upon that law as on the best of friends,"

with men who can find facts and who can face them boldly and honestly.

The engineer's work has started many trends in the direction of relief from some of the world's growing difficulties. A notable one is the spread of electric power into areas away from congestion, thereby permitting at least a partial decentralization of industries and of population. This spread is greatly advanced by the interconnection of power systems now so common all over the country, while the ease of getting about with automobiles is another important factor. A further material aid is the extension of electric distribution lines into rural regions so that modern methods can be applied increasingly to agriculture, both in the field and in the home, while the telephone and radio

3. "Whither Mankind" edited by Charles A. Beard.

are keeping farm operators in touch with the latest in music and education. Great as the progress has been, much still remains to be done in these fields.

Among other items that bring cheer and stimulate optimism may be mentioned the increasing interest now being taken in sane city and regional planning, the efforts of important industries looking toward elimination of waste and the conservation of our resources, the conversion of former wastes into profitable by-products and particularly the growing reclamation of wastes in agriculture.

But here is a bit of pessimism.—The high speed at which life seems to be driven today and the apparent immersion of large numbers in gross materialism has filled some people with fear and misgivings regarding the future. Thus we have the Bishop of Ripon seriously suggesting a ten year holiday in science to give the culture of the soul an opportunity to catch up with the rapid material progress. But the fear that the "spirit" cannot grow in an atmosphere of "science" is not a new one. A century ago Edgar Allen Poe in his Sonnet to Science wrote in part

"Hast thou not dragged Diana from her car,
And driven the hamadryad from the wood
To seek shelter in some happier star?
Hast thou not torn the naiad from her flood,
....."

The feeling that our present material progress is not really making for a richer life is expressed by many more. Even our own Lorado Taft, with a fine enthusiasm for beauty and an outstanding genius for creating it, is led by his observation to conclude that Americans are practically immune to the arts, have no joy in creating, and are not interested in the most important thing of all, the creation of an ideal civilization.

What answer have we engineer optimists to these critics?—

The good bishop sees but a small part of the picture and that not the bright and inspiring part. When the young Poe wrote his sonnet the Age of Electricity had not dawned. His hamadryads and naiads would today be quite at home with most of our scientists and engineers. And our gifted sculptor seems to feel that the progress made through technology expresses itself mainly in jazz. He fails apparently to see the poetry in the work of a Millikan, a Langmuir, a Steinmetz, or an Edison. He should see, as Pupin and others so clearly see, the idealism of the American machine.

The engineer with his enthusiasm over the human purpose of technology's accomplishments is guided by

his ideal of a better living for man, but he keeps his feet on the ground in a practical effort to reach this goal step by step. He appreciates that

"Heaven is not reached by a single bound;
But we build the ladder by which we rise
From the lowly earth to the vaulted skies,
And we mount to its summit round by round."

The important thing is to be mounting the rounds. That we are moving onward and upward I for one firmly believe.

Is not one true indication of the direction in which we are moving found in the growing appreciation of beauty? The advertising pages of our magazines clearly show the turn of the tide. On every hand commercial competition seems to be along lines of greatest devotion to a beautiful product, and this is not confined to automobiles and bathroom fixtures. Art, which Henry James called "the shadow of humanity," is at last finding its place in industry.

The engineer accepts the line from Keat's famous Ode

"Beauty is truth, truth beauty."

He is conscious of the beauty and the romance in many of the facts he deals with but he does not let his enthusiasm over the beauty, or his dreaming stirred by the romance, blind him to a proper weighing of the facts. Rather he develops from his dreaming a use of the facts for the further enrichment of life.

And what of the engineer of tomorrow? What thought are we giving to him? Engineers appreciate that by their example, as well as by their encouragement and active help given to educators and to the engineering novitiate, they are building the foundations of the profession more firmly and raising it ever higher. They know that education for useful living is not completed in college. It continues throughout life.

Our Institute, representing the electrical section of American engineers, offers the fellowship of kindred souls, a broadening of outlook and of knowledge, a blending of humanism with technology. It carries inspiration to its members to be not only technicians of high order but also trained seekers of the needs of mankind, applying their skill and their knowledge to the end that life for the teeming millions of their fellowmen may be made more worth while, less burdensome, more healthful, and more noble.

Thus, my friends, do I conceive the true engineer,—one, who in thought and deed, is and ever will be a practical idealist.

Current Transformer Excitation Under Transit Conditions

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Synopsis.—Tests of circuit breakers, relays, and similar devices in which current transformers have been used to step down the large currents involved to values measurable by the oscillograph, have shown peculiar errors in the records during the transient portion of the current wave.

The purpose of this paper is to show that the abnormal excitation

of the magnetic circuit of the current transformer required during transient conditions is the cause of these errors, and to point out how the errors may be minimized sufficiently to be negligible.

Mathematical expressions are also derived to make it possible to predetermine the ability of a transformer to handle transients correctly and to guide in the design of transformers for this service.

THIS paper is closely related to the problem of the measurement of transient alternating currents.

When certain apparatus such as circuit breakers are subject to short circuit tests, it is desirable to have a correct indication of current during the transient condition.

In the past, two methods have been used for measuring heavy transient currents, namely, the non-inductive shunt and the current transformer. Considerable field testing has demonstrated that these methods have introduced difficulty under some conditions. When the shunt is used it is of course necessary to insulate it and associated oscillograph apparatus from ground to the extent of full line voltage. Furthermore, non-inductive shunts can be used only with non-inductive measuring devices and therefore cannot be used with the current coil of watt oscillograph elements, which are highly inductive, for the measurement of instantaneous power.

Even with resistive burdens inaccuracies will result due both to self inductance and mutual inductance on multi-phase set-ups.

The use of the current transformer for the measurement of transients has resulted in some inaccuracies under certain conditions. In this paper efforts have been made to determine the causes of the errors which occur, the extent of the errors, and their elimination or minimization. The causes of the errors are first briefly outlined. A discussion of the practical importance of the errors is given. A mathematical exposition of the theory is given, including the formulas for designing transformers having suitable characteristics for the measurement of transients. A number of oscillograph records, amplifying and checking the theory, is presented, and finally a method is given for testing transformers to determine their suitability for use under transient conditions.

The authors are indebted to Mr. J. F. Peters for constructive criticism and to Mr. L. R. Smith for assistance given in conducting the tests.

OUTLINE OF CAUSES OF ERRORS AND THEIR CHARACTERISTICS

If the circuit in which the primary of the current

*Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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transformer is connected contains both resistance and inductance the current flowing in that circuit, just after its switch is closed, will not always immediately assume a pure sinusoidal wave form but will be displaced from its normal zero axis in a manner similar to the current curve shown in Fig. 1. (For equation of this curve see Equation (4) in the Mathematical Exposition.)

This asymmetry rapidly decreases and in practical circuits disappears in about 3 to 15 cycles of 60-cycle current. The degree of asymmetry depends on the

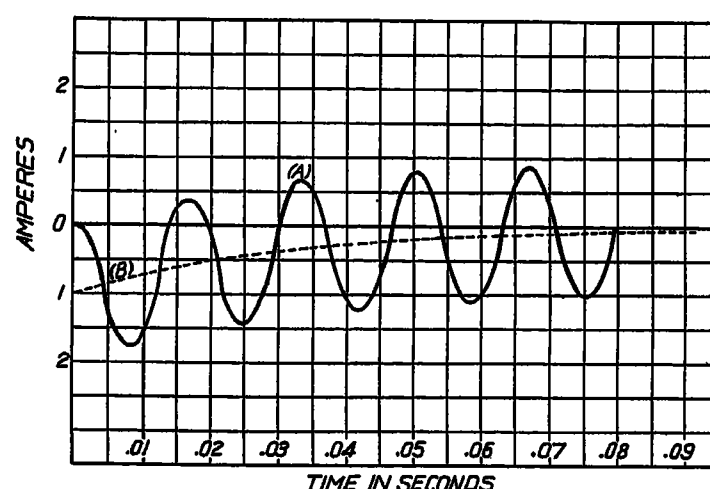


FIG. 1—TRANSIENT CURRENT FOR INDUCTIVE CIRCUIT HAVING TIME CONSTANT 0.0304 AT 60 CYCLES

(A) = Asymmetrical current wave
(B) = Displaced zero axis

point of the voltage wave at which the switch is closed. The current wave is practically normal if the switch is closed when the voltage is at its maximum and may be entirely above or below the zero line, if the switch is closed at the zero of the voltage wave. The point on the voltage wave at which the switch is closed is usually a matter of chance, although it is sometimes argued that inasmuch as in high-voltage circuits the current might start before the switch is completely closed, the first case is the more probable. Thus in the majority of cases, the transient will be comparatively slight. (Fig. 1 is calculated on the basis of a closure under the worst possible conditions.)

The important thing to appreciate, as far as this paper is concerned, is that this dissymmetry is quite likely to occur just after the switch is closed. This paper therefore treats of the effect of the dissymmetry on the mag-

netizing current and the resultant error in a current transformer under such transient conditions.

The error is due to the over-saturation of the transformer which is caused by the d-c. component of the asymmetrical current. This condition is of course aggravated if the secondary burden is excessive. The error in transformation will vary also, depending upon the amount of residual magnetism and its polarity with respect to that of the d-c. component. For this reason, in tests where accuracy is essential, the transformer selected for use in measuring transients must be designed for a low degree of saturation at the burden to be imposed and must be demagnetized between successive heavy shots. On tests which do not come up to the knee of the saturation curve, the residual will probably be so slight that demagnetization will not be required.

A mathematical solution of the problem, based on certain assumptions, which derives expressions for the wave form of the transformer magnetizing current and which gives formulas for use in applying and designing transformers for this service, is given under the heading of Mathematical Exposition. An absolutely rigid solution of the problem for an iron core transformer is impossible but enough can be done mathematically to throw considerable light on the problem. The equations and the data indicate that the inaccuracies of the current transformer during unsymmetrical transients are caused by the large flux required to generate the voltage necessary to reproduce the transient in the burden of the transformer. The maximum value of transient flux is dependent on the magnitude of the current, the duration of the transient, the design of the transformer, and the secondary burden.

A series of tests was made to check and amplify the mathematical theory and the data thus secured are given under the heading of Test Data in this paper.

PRACTICAL IMPORTANCE OF ERRORS

As these errors are caused by the dissymmetry of the primary current which is dependent on the cyclic time of closing the switch, their appearance is rather uncertain, but always possible, and may cause erroneous conclusions on an important test.

The magnitude of these errors is generally comparatively slight, although on extremely heavy short circuits of a high degree of asymmetry, with a particularly unsuitable transformer having a heavy secondary burden, the degree of over-saturation may be so great as to cause an error of roughly 50 per cent in the r. m. s. value of the first current wave. The most noticeable effect of the errors is the distortion of the secondary current wave shape rather than serious diminution of the crest value.

In most cases the error thus introduced is comparatively unimportant except in the cases of high speed relay operation and watt oscillographs. The great majority of tests to determine rupturing capacity of

circuit breakers are so made that the current has reached a steady state condition before arcing starts. Even though this condition has not been reached, the r. m. s. current of the first half cycle of arcing is usually determined from the crest value, with due allowance for the displacement of the neutral axis, on the assumption that the wave is of sinusoidal shape which partially corrects for the error but always indicates a lower current than actually occurred.

In oscillograph testing, however, the accuracy required is not of as high an order as required for current transformers used with watthour meters, hence the allowable flux density is higher. The oscillograph burden is lower than the usual burdens. These two factors tend to compensate for the high value of transient flux required, thus making the problem of applying or designing a suitable current transformer less difficult than might appear.

The only competitor of the current transformer has been the non-inductive shunt. This method, however, presents difficult insulation problems as the oscillograph elements must be directly connected to the high-voltage lines.¹ It should also be fully appreciated that a non-inductive shunt is only allowable for use with non-inductive burdens. It must always be of the same time constant as the burden. This effect is not serious for straight current measuring oscillograph elements. Watt oscillograph elements, however, having current coils of relatively high inductance, can not be used with non-inductive shunts.

The current transformer works better, if anything, for inductive than for resistive burdens and may be used for any type of element. Against the disadvantages of demagnetizing transformers may be set the added safety to operators, the lack of necessity of insulating the operator and instrument from ground, and the possibility of using the transformers supplied in the apparatus under test instead of special equipment.

MATHEMATICAL EXPOSITION

In any transformer the flux, voltage, time, relative in a form independent of wave form is:

$$e = N \frac{d\phi}{dt} 10^{-8}, \text{ or } \phi = \frac{10^8}{N} \int e dt + c \quad (1)$$

where

e = instantaneous volts as a function of time.

ϕ = flux lines.

N = number of turns in coil threaded by and generating e .

t = time in seconds.

c = a constant depending on value of ϕ at zero time.

Thus to calculate the flux threading a coil generating a known time wave of voltage it is necessary to integrate the voltage-time relation from the time when the voltage started. In other words, the flux through the coil

1. For references see Bibliography.

at any time is proportional to the area under the voltage time curve from the time when it started to the given time.

There are two practical methods of calculating the voltage in the secondary winding of a current transformer when a given current flows in the primary winding. The first way (a) is to assume that the magnetizing current is negligible and that therefore the secondary voltage is equal to the primary current divided by the transformer ratio multiplied by the secondary circuit impedance. The second way (b), is to make use of a so-called equivalent transformer circuit.

The first method is obviously the least accurate but has the great advantage of simplicity; it is equivalent to calculating the flux of an "ideal" transformer, that is, one having a magnetic circuit of zero reluctance. As this condition defines the limits of the problem we shall use it first.

Mathematical Solution (a)

As we are assuming that

$$i_s = i_p \frac{N_p}{N_s} \quad (2)$$

Where

$$\begin{aligned} i_s &= \text{secondary current} \\ i_p &= \text{primary current} \\ N_s &= \text{secondary turns} \\ N_p &= \text{primary turns} \end{aligned}$$

it is evident that Equation (2) for this case will take on the form:

$$\begin{aligned} \phi &= \frac{10^8 N_p}{N_s^2} \int \left(R_2 i_p + L_2 \frac{d i_p}{d t} \right) d t + c \\ &= \frac{10^8 N_p}{N_s^2} \left[\int R_2 i_p d t + L_2 i_p + c \right] \end{aligned} \quad (3)$$

where R_2 and L_2 are secondary resistance and inductance respectively.

If we consider the case of an unsymmetrical transient such as occurs on transmission lines and other circuits containing resistance and inductance in series, we shall substitute for the primary current:

$$i_p = I \left[\sin (\omega t + \alpha) - \sin \alpha e^{-\frac{t}{T}} \right] \quad (4)$$

where:

i = instantaneous current at time (t).

I = maximum value of steady state current.

$\alpha = \left(\theta - \tan^{-1} \frac{\omega L}{R} \right)$ phase angle which fixes value of instantaneous volts when ($t = 0$). For maximum transient, $\alpha = \frac{\pi}{2}$.

T = time constant = $\frac{L}{R}$ of total primary circuit.

After performing the indicated operations, the expression for flux in the transformer core becomes:

$$\begin{aligned} \phi &= \frac{10^8 N_p}{N_s^2} I_p \left[\frac{1}{\omega} \sqrt{R_2^2 + \omega^2 L_2^2} \sin \left[\omega t \right. \right. \\ &\quad \left. \left. + \alpha - \tan^{-1} \left(\frac{R_2}{\omega L_2} \right) \right] + (R_2 T - L_2) \sin \alpha e^{-\frac{t}{T}} + C \right] \end{aligned} \quad (5)$$

As pointed out above the dissymmetry is at its maximum when the switch energizing the primary circuit is closed at the time when $\alpha = 90$ deg. Hence the flux for maximum transient is:

$$\begin{aligned} \phi &= \frac{10^8 N_p}{N_s^2} I_p \left[\frac{1}{\omega} \sqrt{R_2^2 + \omega^2 L_2^2} \sin \left(\omega t \right. \right. \\ &\quad \left. \left. + \tan^{-1} \frac{\omega L_2}{R_2} \right) - R_2 T (1 - e^{-\frac{t}{T}}) - L_2 e^{-\frac{t}{T}} \right] \end{aligned} \quad (6)$$

The constant (c) is solved for on the basis that ($\phi = 0$) when ($t = 0$)

This expression consists of the usual steady state

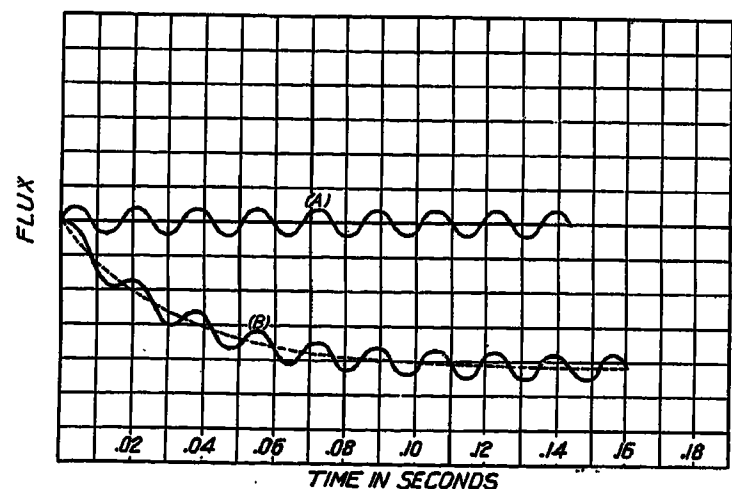


FIG. 2—WAVE FORM OF FLUX REQUIRED TO REPRODUCE EXACTLY TRANSIENT OF FIG. 1

(A) = Flux caused by steady state current
(B) = Flux caused by transient current

sine wave term and an exponential term which is caused by the dissymmetry of the primary current wave. A curve of this wave shape is plotted in Fig. 2, the dotted curve being the shape of the exponential term, to which is added the sine term in heavy line. The ordinary steady state flux is also shown, plotted for comparison about the zero line.

Expression (6) reaches its maximum when $t = \infty$ and is equal then to:

$$\phi_{max} = \frac{10^8 N_p}{N_s^2} I_p \left[\frac{1}{\omega} \sqrt{R_2^2 + \omega^2 L_2^2} + R_2 T \right] \quad (7)$$

This expression gives the magnitude of the maximum flux without regard to sign. It will be noticed that the secondary inductance of the transformer has

no effect on the maximum transient flux. Its only effect is on the steady state.

For the usual case of a ring type transformer having a well distributed secondary winding connected to an oscillograph, the secondary inductance is negligible,⁴ and by assuming it equal to 0 in Equation (7),

$$\phi_{max} = \frac{10^8 N_p}{N_s^2} I_p \frac{R_2}{\omega} [1 + \omega T]. \quad (8)$$

but the portion preceding the brackets is equal to the steady state flux so that the latter part can be called the transient flux multiplier:

$$m_1 = [1 + \omega T] \quad (9)$$

This simple expression is of value in judging the severity of a transient as regards the saturation of the current transformer cores, as it required no knowledge of the transformer constants.

Mathematical Solution (b)

The second method of solution, by equivalent circuits, fits the case much closer than the first method but is considerably more involved. It will, however, give equations for magnetizing currents which are closely borne out by oscillograph records, and equations may be derived which give quite accurate values for errors and maximum flux values as they are affected by the constants of the transformer itself.

It assumes a non-saturated transformer and neglects the hysteresis and eddy current effects. This assumption is not serious because the transient portion of the flux is practically unidirectional and saturated transformers are out of the question entirely. It should be appreciated that where equivalent circuits are used

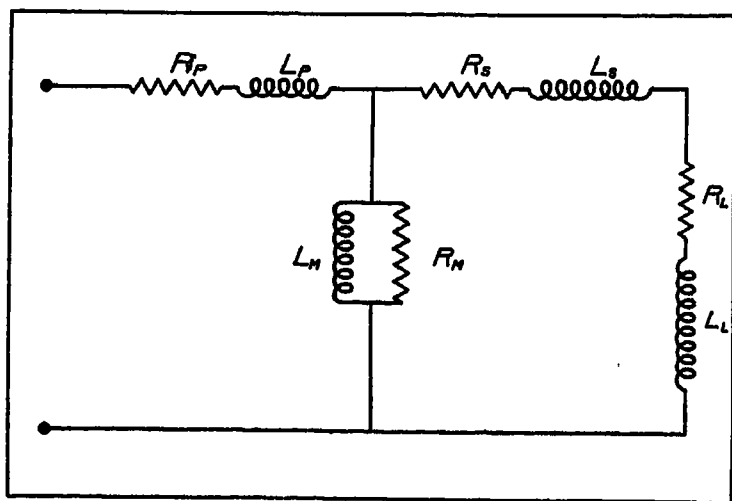


FIG. 3—EQUIVALENT CIRCUIT OF A VOLTAGE TRANSFORMER

we shall speak of magnetizing current instead of flux on the basis that they are directly proportional.

The transformer may be considered as equivalent to the circuit of Fig. 3

where:

- R_p = resistance of primary.
- L_p = inductance of primary.
- R_m = equivalent iron loss shunt resistance.
- L_m = equivalent magnetizing shunt inductance.
- R_s = resistance of secondary.

L_s = inductance of secondary.

R_L = burden resistance.

L_L = burden inductance.

The above equivalent circuit is the one given by standard text books,² and applies to transformers operating with constant voltage applied to the primary winding. If the current in the primary winding is known, then R_p and L_p are no longer of interest in determining the secondary current. When the iron loss is considered as negligible, the resistance R_m is infinite and the equivalent circuit for the current transformer therefore reduces to the circuit of Fig. 4 where $R_2 = R_s + R_L$ and $L_2 = L_s + L_L$. For con-

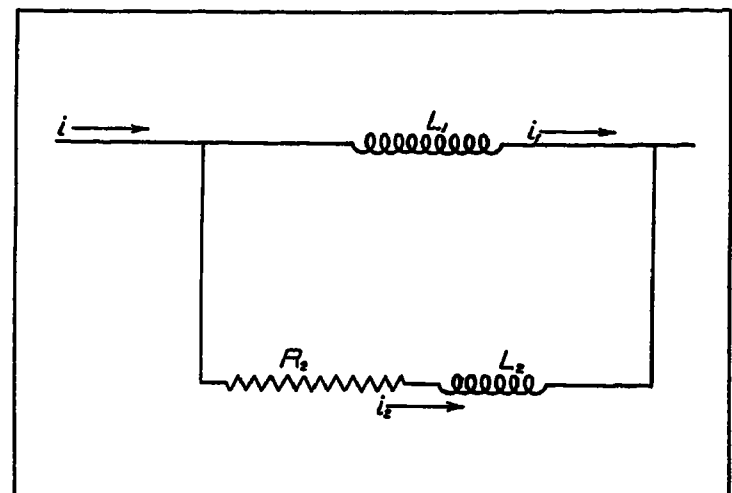


FIG. 4—EQUIVALENT CIRCUIT OF A CURRENT TRANSFORMER CONSIDERING THE IRON LOSS NEGLIGIBLE

venience we shall call the magnetizing inductance L_1 , thus $L_1 = L_m$. The primary current is i , the magnetizing current i_1 , and the burden current i_2 (referred to secondary).

To solve for the division of currents we write the following equations:

$$L_1 \frac{d i_1}{d t} = R_2 i_2 + L_2 \frac{d i_2}{d t} \quad (10)$$

$$i_2 = i - i_1 \quad (11)$$

From (10) and (11)

$$\frac{d i_1}{d t} + \frac{R_2}{L_1 + L_2} i_1 = \frac{1}{L_1 + L_2} \left(L_2 \frac{d i}{d t} + R_2 i \right) \quad (12)$$

The general solution³ of this type of differential equation is:

$$i_1 = \frac{1}{L_1 + L_2} e^{\frac{-R_2 t}{L_1 + L_2}} \int \left[\left(R_2 i + L_2 \frac{d i}{d t} \right) e^{\frac{R_2 t}{L_1 + L_2}} \right] d t + c e^{\frac{-R_2 t}{L_1 + L_2}} \quad (13)$$

where i equals any function of time. To simplify the writing of the exponent we shall indicate the quantity:

$$\frac{R_2}{L_1 + L_2} = \frac{1}{T_1} \quad (14)$$

Hence (13) becomes:

$$i_1 = R_2 T_1 \epsilon^{\frac{-t}{T_1}} \int \left(R_2 i + L_2 \frac{di}{dt} \right) \epsilon^{\frac{t}{T_1}} dt + c \epsilon^{\frac{-t}{T_1}} \quad (15)$$

By the use of this equation we may determine the magnetizing current wave shape for any shape of primary current, providing of course that the resulting expression is possible to integrate.

CASE OF PRIMARY CURRENT CONTAINING UNSYMMETRICAL TRANSIENT

If the primary current is unsymmetrical it may be represented by the following equation as given earlier in the paper.

$$i = I [\sin(\omega t + \alpha) - \sin \alpha \epsilon^{\frac{-t}{T}}]$$

See Fig. 1.

If this expression is substituted in (15) the equation for the magnetizing current will be found to be:

$$i_1 = I \left\{ \frac{\sqrt{R_2^2 + \omega^2 L_2^2}}{R_2 \sqrt{1 + \omega^2 T_1^2}} \left[\sin(\omega t + \alpha + \phi - \Delta) - \sin(\alpha + \phi - \Delta) \epsilon^{\frac{-t}{T_1}} \right] + \frac{L_2 - R_2 T}{R_2 (T - T_1)} \sin \alpha \left(\epsilon^{\frac{-t}{T}} - \epsilon^{\frac{-t}{T_1}} \right) \right\}$$

$$T_1 = \frac{L_1 + L_2}{R_2}; \tan \phi = \frac{\omega L_2}{R_2}; \tan \Delta = T_1 \omega; (i_1 = 0), (t = 0). \quad (16)$$

This expression is plotted for a given set of more or

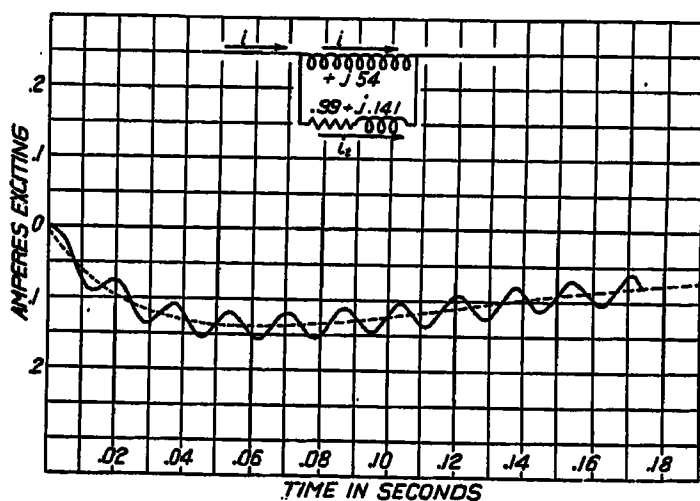


FIG. 5—MAGNETIZING CURRENT FOR TRANSIENT OF FIG. 1. TRANSFORMER CONSTANTS AS SHOWN IN EQUIVALENT CIRCUIT AND ASSUMING STRAIGHT LINE SATURATION

less arbitrary constants in Fig. 5. It will be noticed that the equation is divided into three parts, the ordinary steady-state sine wave of magnetizing current, the transient term, and a third term whose function it is to make the value of magnetizing current zero at zero time. The last two terms combine in the form $A \epsilon^{\frac{-t}{T}} - (A + B) \epsilon^{\frac{-t}{T_1}}$ (17) which is shown as the dotted curve in Fig. 5, to which is added the steady-state magnetizing current drawn as a solid line. It is this transient term which may add so much to the flux required in the transformer core during the transient

period of the primary current that causes all the trouble through saturation at that time.

By comparing Fig. 5 with Fig. 2, in which the flux required in an ideal transformer (one having zero reluctance in its magnetic circuit) is shown, it may be seen that the actual transformer tries to follow the action of the ideal, but cannot due to the necessity of its drawing the large unidirectional magnetizing current required from the primary current. The primary current has but a small unidirectional current and hence cannot supply the unidirectional magnetizing current required by the transformer. The magnetizing cur-

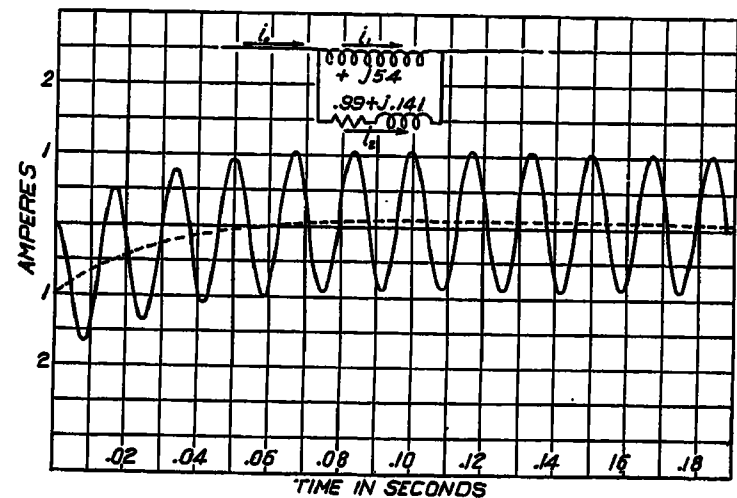


FIG. 6—SECONDARY CURRENT FOR TRANSIENT OF FIG. 1. TRANSFORMER CONSTANTS AS SHOWN IN EQUIVALENT CIRCUIT AND ASSUMING STRAIGHT LINE SATURATION. PLOTTED FROM DIFFERENCE OF FIGS. 1 AND 5

rent must therefore fall gradually to zero. This decreasing flux generates a unidirectional voltage which causes a current through the burden circuit. This current enables the flux to gradually decrease to steady state form and also causes an apparent shift in the zero line of the secondary current which is clearly noticeable in Fig. 6. Thus the fact that the ideal magnetizing current requirements cannot be met results in a secondary current of higher decrement than the primary current and an apparent shift of its zero line.

The reader should bear in mind that the foregoing equations are derived on the assumption of constant permeability of the iron core. If the core becomes saturated the exciting current would look more like the upper curve in Fig. 7.

The above expression (16) is general, that is, it contains provisions for both variation in the shape of the primary current transient as affected by variations in the phase at which the main circuit is closed, and also provision for an inductive burden. If now we make an assumption of no secondary leakage inductance, which is justified on the ground that the oscillographic circuits and the through ring type transformers with which we are mainly concerned are very closely non-inductive,⁴ and that the inductance which is present in the secondary circuit has but small effect on the transient flux, we

can deduce several expressions which will prove useful in the design of transformers for this service.

If we substitute in Equation (16) the following:
 $L_2 = 0$, $\sin \alpha = 1$, (which causes maximum primary transient),
 we have:

$$i_1 = I \left[\frac{1}{\sqrt{1 + \omega^2 T_1^2}} \cos (\omega t - \tan^{-1} \omega T_1) - \frac{T}{T - T_1} \left(e^{-\frac{t}{T}} - e^{-\frac{t}{T_1}} \right) + \frac{e^{-\frac{t}{T_1}}}{1 + \omega^2 T_1^2} \right] \quad (18)$$

which give the shape of the magnetizing current as a

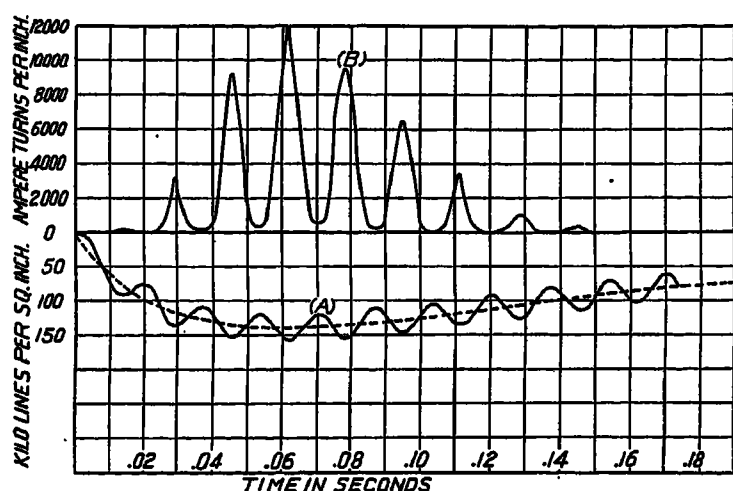


FIG. 7—AMPERE TURNS REQUIRED TO PRODUCE FLUX OF FIG. 5

(Hysteresis assumed negligible)

(A) = Flux wave

(B) = Ampere turns to produce flux in curve A assuming saturation

function of $(T_1) = \frac{L_1}{R_2}$. This factor is easily calcu-

lated from the magnetizing current-voltage characteristic of the transformer, and the total secondary resistance.

Maximum Value of Transient Flux. As given before the transient term may be represented by Equation (17):

$$A e^{-\frac{t}{T}} - (A + B) e^{-\frac{t}{T_1}} = u$$

where u represents the transient portion of the magnetizing current. Differentiating (17) and equating to zero, we find that

$$t = \log_e \left[\frac{T_1}{T} \frac{A}{A + B} \right]^{\frac{T T_1}{T_1 - T}} \quad (19)$$

which is the time at which the transient term reaches its maximum value.

Substituting this expression in Equation (17) we have for the maximum value of the transient magnetizing current:

$$U_{max} = A \left[\frac{T_1}{T} \frac{A}{A + B} \right]^{\frac{-T_1}{T_1 - T}} (A + B) \left[\frac{T_1}{T} \frac{A}{A + B} \right]^{\frac{-T}{T_1 - T}} \quad (20)$$

By substituting the values of the constants of Equation (17) in the above Equation (20), the correct maximum value of the transient magnetizing current will be obtained.

For design purposes Equation (18) is accurate to a high degree. By taking the coefficients as given there and substituting in (20) and by the use of a justifiable assumption the following simpler equation for the maximum is derived:

$$U_{max} = I \left(\frac{T_1}{T} \right)^{\frac{-T_1}{T_1 - T}} \quad (21)$$

where as before,

$T_1 = \frac{L_1}{R_2}$, T = time constant of primary transient,

and I = maximum value of the steady-state primary current.

The assumption is that $\frac{1}{1 + \omega^2 T_1^2} = 0$. This will in general be closely true for all iron core commercial transformers.

The quantity u_{max} is plotted on a percentage basis for three representative values of T as a function of T_1 in Fig. 8, where I is considered as equal to 100 per

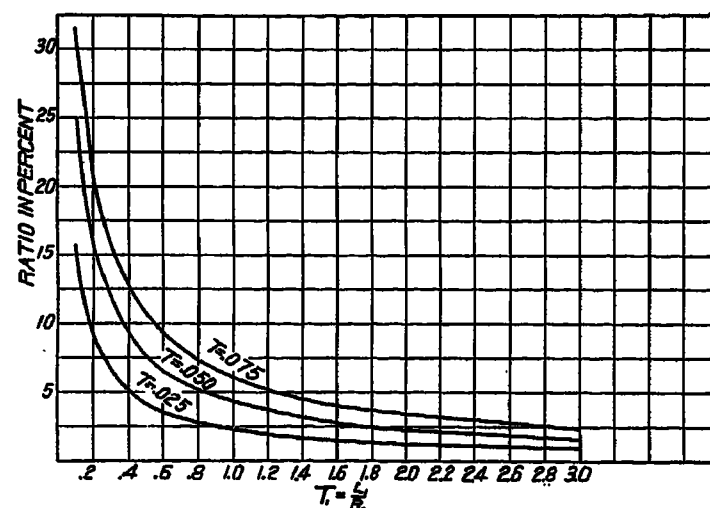


FIG. 8—RATIO OF MAXIMUM TRANSIENT MAGNETIZING CURRENT TO MAXIMUM STEADY STATE PRIMARY CURRENT IN PER CENT FOR DIFFERENT VALUES OF

(T represents time constant of primary circuit)

cent. (I) may be either primary or secondary depending on reference. This equation and the curves give the maximum transient error of the transformer under the foregoing conditions.

By dividing u_{max} by $\frac{I R_2}{\omega L_1}$ (the usual approximation for the steady-state magnetizing current) we obtain a transient flux multiplier similar to the variable part of Equation (9):

$$m_2 = \omega T_1 \left(\frac{T}{T_1} \right)^{\frac{T_1}{T_1 - T}} \quad (22)$$

This multiplier gives the ratio between the maximum

transient flux or exciting current and the steady-state flux or exciting current. This expression is plotted under the same conditions as Equation (21) in Fig. 9. If the ratio of the maximum total transient flux to the steady-state flux is required the expression is:

$$m_1 = \left[\omega T_1 \left(\frac{T}{T_1} \right)^{\frac{T_1}{T_1 - T}} + 1 \right] \quad (23)$$

When T_1 is infinite the transformer is ideal and the above expression reduces to expression (9).

CASE OF PRIMARY CURRENT CONTAINING BOTH SYMMETRICAL AND UNSYMMETRICAL TRANSIENTS

When an alternator is short circuited the armature reaction is in such a direction as to decrease the mag-

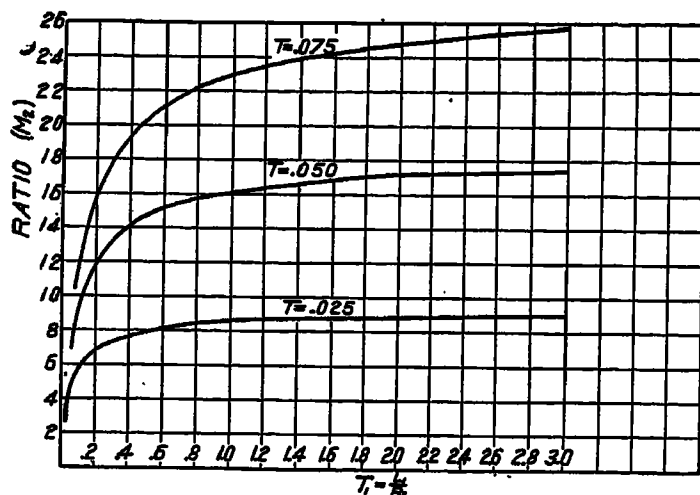


FIG. 9—RATIO OF MAXIMUM TRANSIENT MAGNETIZING CURRENT TO MAXIMUM STEADY STATE MAGNETIZING CURRENT FOR DIFFERENT VALUES OF

(T represents time constant of primary circuit)

netism of the revolving field. This causes the generated voltage to decrease from an initial to a final value exponentially as the flux decreases.⁵

If the short circuit should occur at the time the voltage is approximately zero, there will also in general occur an unsymmetrical transient similar to those encountered before in this paper.

The current flowing under these conditions may be represented by the expression:

$$i = I_2 \left[\sin(\omega t + \alpha) - \sin \alpha e^{\frac{-Rt}{L}} \right] + I_1 \left[e^{\frac{-t}{T_2}} \sin(\omega t + \beta) - \sin \beta e^{\frac{-Rt}{L}} \right] \quad (24)$$

$$\alpha = \left(\phi - \tan^{-1} \frac{\omega L}{R} \right); \quad \beta = \left(\phi - \tan^{-1} \frac{\omega L T_2}{R T_2 - L} \right).$$

If this current is passed through the transformer the magnetizing current is given by:

$$i_1 = \frac{A e^{\frac{-t}{T_2}}}{\sqrt{\left(1 + \frac{T_1}{T_2}\right)^2 + \omega^2 T_1^2}} \left[\sin(\omega t + \beta - \gamma) \right]$$

$$+ \frac{B}{\sqrt{1 + \omega^2 T_1^2}} [\sin(\omega t + \alpha - \Delta)] - \frac{C T}{T - T_1} \sin \alpha \left(e^{\frac{-t}{T}} - e^{\frac{-t}{T_1}} \right) + D e^{\frac{-t}{T_1}}.$$

$$\tan \gamma = \frac{\omega T_2 T_1}{T_2 - T_1}; \quad \tan \Delta = \omega T_1.$$

There is no simple method of finding the maximum of this equation, but it will be noticed that the only term that can cause a very high rise of flux is the third term.

This term is the same on which our previous operations for maximum were made and therefore we may safely state that conclusions arrived at previously for maximum flux values in unsymmetrical cases may be applied to cases containing both symmetrical and unsymmetrical transients by simply neglecting the alternator decrement.

TEST DATA

As a check on the theory, a series of tests was made on several through type current transformers. For the purpose of separating the exciting current component from the primary current a scheme shown in Fig. 10 was used. A primary circuit was set up to have definite pre-determined values of resistance and inductance such that transients of definitely known time constant, (T), could be obtained. Non-inductive

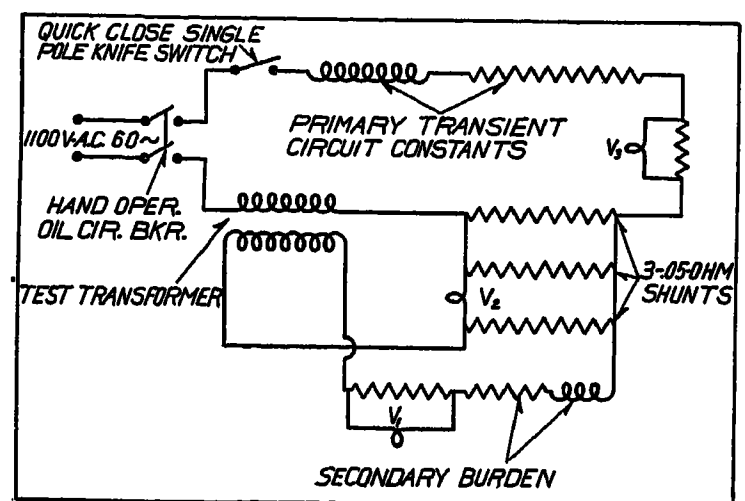


FIG. 10—SCHEMATIC DIAGRAM OF TRANSIENT TESTING CIRCUIT

shunts were used in parallel with the oscillograph elements V_1 and V_3 to obtain the total secondary current and the total primary current. A combination of three shunts of equal value was used in the differential circuit with oscillograph element V_2 for the purpose of obtaining the difference between the primary and secondary currents. As the ratio of the transformer is 2 to 1 and as the resistance of element V_2 is high in comparison with the resistance of the shunts, the deflection of the element V_2 will be proportional to the difference between the primary and secondary currents, thus giving a measure of the exciting current or instantaneous error of the transformer.

The circuit supply of 1100 volts, 60 cycles was controlled by a hand operated oil circuit breaker and a synchronized switching arrangement. As illustrated in Fig. 10, the control of the quick-close, single-pole knife switch (short circulating switch) was so arranged as to make it possible to start the transient on any part of the voltage wave. The control of the oscillograph allowed the shutter to be opened, the film to start moving, and the synchronous switch to operate all in correct sequence, thus insuring a film with the proper transient well spaced each time. For the tests described herein the transient was started at the point on the voltage wave which caused the maximum dissymmetry of current. The drum driven by the synchronous motor was also provided with a stroboscope arrangement in conjunction with a neon lamp for the purpose of checking synchronism and also for easy reversal of successive transients on OCO test.

The transformer used for these tests was a ring type constructed to fit the standard 37,000-volt condenser type bushing having design constants:

- (a) Secondary turns.....100
- (b) Core diameter inside.....4³/₈ in.
- (c) Core diameter outside.....6¹/₈ in.
- (d) Core cross sectional area 4.26 sq. in.
- (e) Secondary resistance.....0.1668 ohms.
- (f) Saturation characteristic (referred to secondary).

Amperes	Volts
0.2	32
0.5	73
1.0	90
2.0	99
8.0	112 ₁

By short circuit impedance test of the transformer

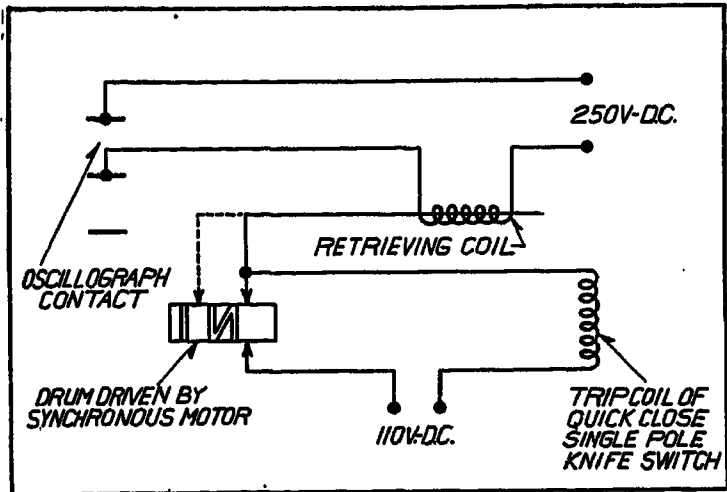


FIG. 11—SCHEMATIC DIAGRAM OF SYNCHRONOUS SWITCHING ARRANGEMENT

with wound primary it was determined that the leakage inductance of both primary and secondary is exceedingly small, power factor 99 per cent, thus justifying the assumption made in the theory of zero leakage inductance.

To allow the use of the measuring scheme of Fig. 10, it was found necessary to use relatively low values of current. Thus, to simulate the actual transformer

performance under heavy short circuits, it was necessary to wind a primary of 50 symmetrically spaced turns on the transformer, thus giving the effect of 800 amperes, (800 ampere turns).

Numerous tests were made under various conditions of circuits and transformer which are outlined as follows:

1. The instantaneous current waves were obtained for several different secondary burdens and primary currents.
2. The instantaneous exciting current waves for

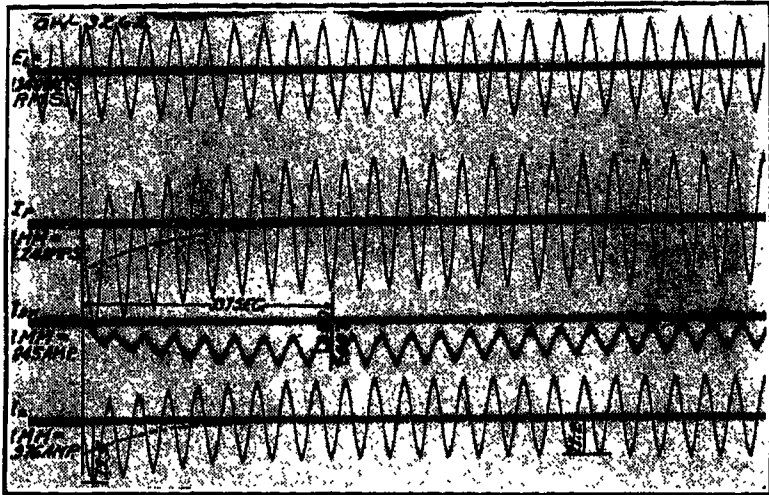


FIG. 12—OSCILLOGRAM OF OC TRANSIENT WITH OSCILLOGRAPH AND SHUNT BURDEN

various transient circuits were investigated by varying the constants of the primary circuit and by varying the instant of start of the transient with respect to the voltage wave.

3. The effect of varying degrees of residual magnetization was determined by magnetizing the test transformer with different values of direct current before subjecting it to transient tests.

In all cases oscillograms indicate the supply voltage, primary current, exciting current, and secondary current. This permits of easy inspection of the results regarding the form of transient and the exciting current waves. Most of the tests were made on OC basis; however, the conditions to be expected under OCO conditions were investigated to show the effect of residual flux. In all cases, except as otherwise mentioned, the tested transformer was demagnetized by using gradually decreasing 60-cycle supply. This removes residual magnetism and permits of direct comparison of the data.

The results, in the form of oscillograms, of a few of the tests and their analysis are given individually.

Fig. 12. This oscillogram was taken with the transformer thoroughly demagnetized and approaches closer to the theoretical curves than any of the oscillograms. The primary current is identified as I_p , the secondary by I_s , and the differential or exciting current by I_d . The transient portion of the magnetizing current is well above the zero line. This current gradually dies down to a steady state of very small amplitude symmetrical with respect to the zero line. This film should be compared with Figs. 1, 5, and 6.

The power factor of the primary circuit is 5.77 per cent which corresponds to a time constant (T) of 0.0447. The total secondary circuit resistance including oscillograph shunts is 0.30. Since the exciting current of the transformer is 1 ampere at 90 volts on the "knee" of the saturation curve, then we can determine that the average value of (T_1) in Equation (18) is 0.795.

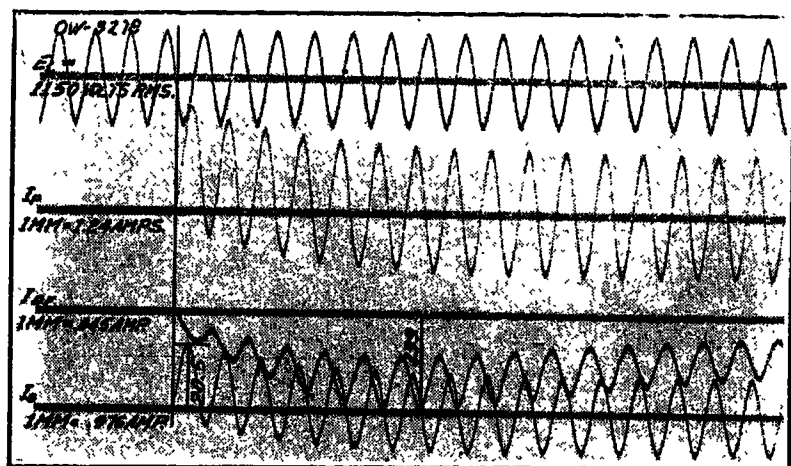


FIG. 13—OSCILLOGRAM OF OC TRANSIENT, PREVIOUSLY MAGNETIZED TRANSFORMER

The time at which the transient portion of the magnetizing current should be a maximum is given by Equation (19). Substituting the value of T_1 calculated above the time obtained is 0.137 seconds. This time is indicated on the film for comparison with the actual maximum as shown on the oscillograph.

The per cent maximum exciting current is given by the expression, Equation (21), which calculated for the above constants is 4.8 per cent. From measurements of the oscillogram, Fig. 12, the secondary current is 11.2 amperes and the maximum transient exciting current is 0.45 ampere, giving a per cent maximum exciting cur-

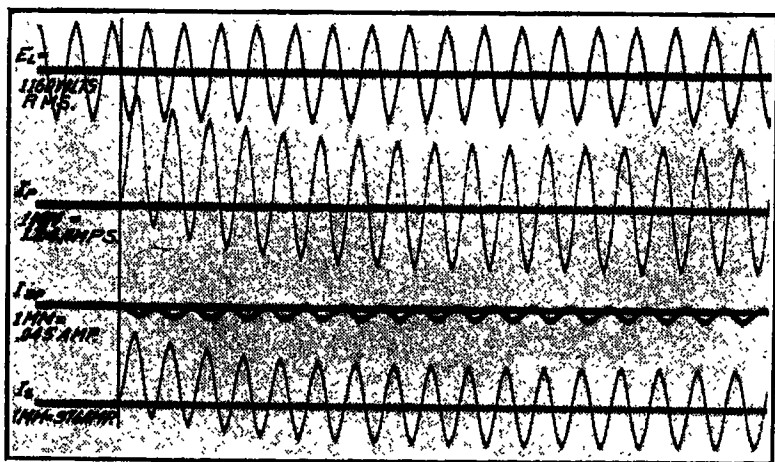


FIG. 14—OSCILLOGRAM OF OC TRANSIENT, PREVIOUSLY MAGNETIZED TRANSFORMER,—POLARITY OPPOSITE TO FIG. 13

rent of 4.02. These values check quite closely when the errors in measurement and oscillograph calibration are taken into account.

Figs. 13 and 14. These are companion oscillograms for the purpose of demonstrating the effect of residual magnetism. The primary and secondary circuit constants are the same as in Fig. 12. Fig. 13 shows the

exciting current transient obtained by previously demagnetizing and then magnetizing the core by a heavy direct current. The record shows the magnetizing current higher than in Fig. 12. As an explanation of

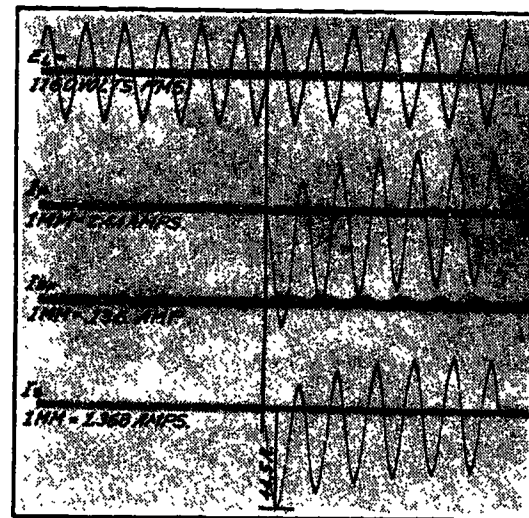


FIG. 15—OSCILLOGRAM OF OCO TRANSIENT WITH OSCILLOGRAPH AND SHUNT BURDEN

this, the presence of the high residual magnetism causes the transformer to work higher up on the hysteresis curve for a few cycles. This of course requires more exciting current to build up the required flux in the transformer. After the transformer is on the circuit for a short time the effect of this residual magnetism disappears.

Fig. 14 illustrates the condition that may be obtained by previously demagnetizing and then magnetizing

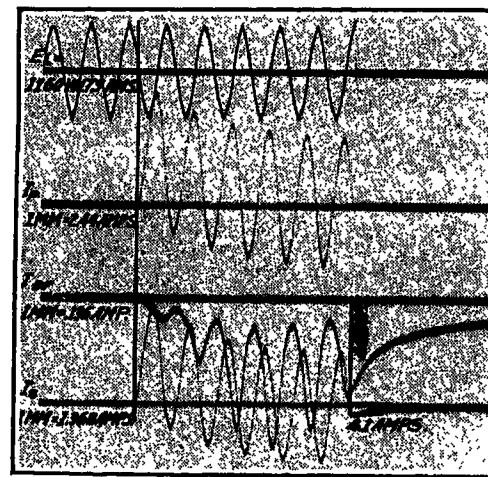


FIG. 16—OSCILLOGRAM OF OCO TRANSIENT STARTING WITH TRANSFORMER IN CONDITION AS AT THE END OF TEST IN FIG. 15

the core oppositely to Fig. 13 and also causing the transient to occur in the same direction. In this case the required transformer flux is built up with a small exciting current, thus approximating steady state value and accuracy.

Figs. 15, 16, and 17. These oscillograms show the results obtained with OCO transients. The primary circuit constants were changed to give a more severe transient. The power factor was changed to 7.46 per cent resulting in the time constant T of 0.0341 and a primary current effect of 1700 amperes. The secondary circuit was the same as in Fig. 12. These three

oscillograms were taken in succession. Before obtaining Fig. 15 the transformer was demagnetized. The test for Fig. 15 was so made that the circuit was opened while the unidirectional flux was still in the core. This flux dies out slowly and leaves a residual.

Fig. 16 shows the effect of the residual flux left after making test indicated in Fig. 15, on the transient magnetizing current. This figure shows a higher value

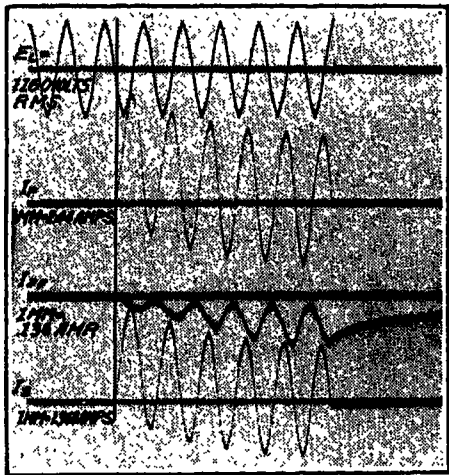


FIG. 17—OSCILLOGRAM OF OCO TRANSIENT STARTING WITH TRANSFORMER IN CONDITION AS AT END OF TEST IN FIG. 16

of exciting current than Fig. 15, thus indicating saturation caused by the preceding residual flux which is a condition similar to that of Fig. 13.

Fig. 17 indicates very little exciting current due to the transient occurring in the opposite direction to the previous transient. This indicates that the residual in this case is a help rather than a hindrance to the magnetization of the core.

An interesting point often encountered in short circuit testing is brought out by Fig. 16. It is noticed

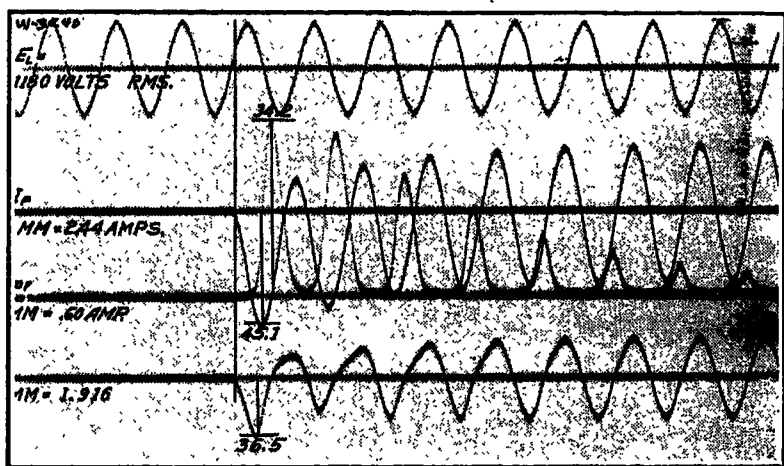


FIG. 18—OSCILLOGRAM OF OC TRANSIENT—SECONDARY BURDEN 1.3 OHMS—MAGNETIZED WITH 2 AMPERES D-C.

that the exciting current slowly falls to zero and causes a current to flow in the secondary after the primary circuit is opened. These two currents must be equal when referred to the secondary as there is no other place for the current generated by the decreasing flux to flow. However, unless the transformer is approaching saturation, this current will be hardly noticeable in the secondary as the exciting current should be a small percentage of the secondary current.

It will be noticed that the alternating component of the exciting current increases considerably as it is added to the unidirectional component. This is caused by the peculiar action of combined alternating and unidirectional flux as brought out in Mr. T. Spooner's book on "Testing and Properties of Magnetic Materials." The flux increases along the conventional magnetization curve until an alternation occurs, when the alternating cycle makes a small hysteresis loop for itself which has a flatter slope than the main hysteresis loop. This has the tendency of increasing the alternating component of the exciting current while not affecting the unidirectional flux to a great extent.

Figs. 18 and 19. These oscillograms illustrate the results that may be obtained under conditions of excessive saturation. The primary circuit was the same as used in Figs. 15, 16, 17. Fig. 18 was taken using a secondary circuit with resistance increased to 1.3 ohms. Before making the test the transformer was demagnetized and then magnetized with 2 amperes direct current applied to the secondary. Fig. 11 was obtained

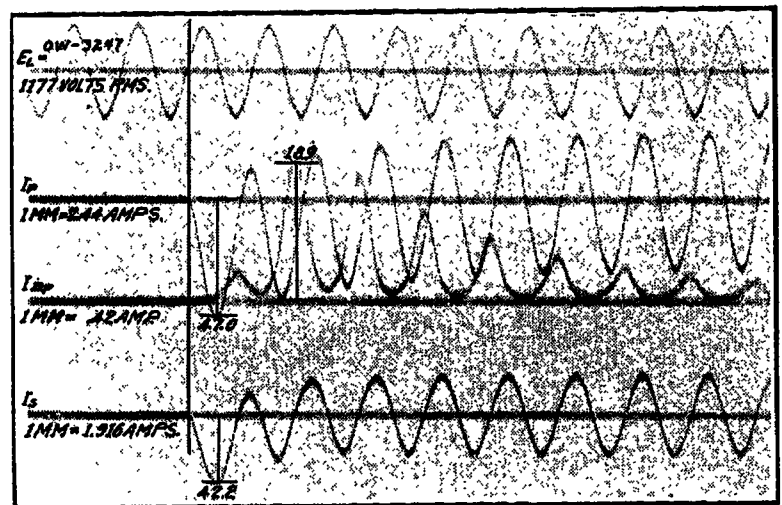


FIG. 19—OSCILLOGRAM OF OC TRANSIENT—SECONDARY BURDEN 0.5 OHM—MAGNETIZED WITH 7 AMPERES D-C.

in a similar manner except the transformer was magnetized with 7 amperes direct current and the secondary circuit resistance was 0.5 ohms. Both oscillograms show excessive saturation as evidenced by the high, comparatively sharp peaked, exciting current wave. They are exhibited here to illustrate how the shape of the exciting transient may be changed by saturation. In addition they also show examples of the wave shape of the secondary current during the transient period obtained with a transformer which saturates during the transient period but is satisfactory for steady state. In the former oscillogram the secondary transient reproduction is considerably disturbed by the exciting transient which rises to maximum peak in the first cycle. If the center line of the transient portion of the secondary current were drawn it would probably come above the zero line as discussed in the theory. I_{af} of Fig. 19 should be compared with the upper curve of Fig. 7.

METHOD OF SELECTING SUITABLE TRANSFORMER

When a current transformer is to be used for short

circuit testing some information should be obtained regarding its adaptability for use on transients before making the tests. It is a relatively simple matter to test a current transformer to determine its suitability for measuring transients. The first operation necessary is to obtain the saturation curve of the transformer by taking readings of volts and amperes into the secondary with the primary circuit open. Then the resistance of the secondary may be measured with a small testing set, to which should be added the oscillograph shunt resistance. (Designate this sum by R_2 .) Using values up to the knee of the saturation curve, divide each voltage by the corresponding current and obtain an average of these results for a value (Z_1). The factor T_1 may be calculated from the following formula:

$$T_1 = \frac{Z_1}{2 \pi f R_2}$$

Calculate the time constant (T) of the primary circuit as the ratio of inductance to resistance of the primary circuit. Knowing (T_1) and (T), the ratio of maximum transient exciting current to maximum secondary steady state current, can be extrapolated from Fig. 8, or calculated from Equation (21). This ratio gives directly the percentage maximum error due to the transient in instantaneous values of secondary current.

Dividing the r. m. s. exciting current just below saturation as obtained from the saturation curve, by the above ratio, will give the r. m. s. value of steady state secondary current which the transformer is capable of handling without excessive errors due to saturation under the given transient conditions.

If the percentage error is within the limits of accuracy desired and if the current to be measured is not greater than the amount calculated above, the transformer should be satisfactory for use in that transient test. The authors' experience has been that the calibration and measurement of oscillograph films give

results of an average accuracy of ± 5 per cent. The transformers should be of about the same order of accuracy.

If transient tests are to be made in fairly close succession and especially for heavy OCO transients, the transformers should be demagnetized before each test. This is easily done by arranging the current transformer circuits to allow them to be easily switched from the oscillograph elements to a source of alternating current of a value comparable to the saturation current obtained previously. This current should then be smoothly reduced to zero by the use of slide wire resistors or their equivalent. In general, if the source of power is 110 volts, two resistances will be required in series, one of the magnitude of 0 to 50 ohms and the other from 0 to 500 ohms. The first should be of sufficient capacity for saturation current, and the second should introduce enough resistance to reduce the current to a minimum value for thorough demagnetization.

At first thought the demagnetizing operation would seem an added burden to the complexities of oscillographic testing. However, if a source of low voltage alternating current is available the arrangement of the demagnetizing circuits adds but little to the set-up and its use becomes a small matter of extra routine on the part of the oscillograph operators.

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